# Principles of Electricity

applied to

# Telephone and Telegraph Work

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AMERICAN TELEPHONE AND TELEGRAPH COMPANY

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applied to

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A Training Course Text

Prepared for Employees of the

Long Lines Department
AMERICAN TELEPHONE AND TELEGRAPH COMPANY

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# PREFACE

A SET of training course notes bearing the title "Elements of Electricity Applied to Telephone and Telegraph Work" and more commonly known as "Training Course No. 2" was issued in 1922 in response to a long-standing demand by Long Lines employees for text material that would demonstrate the fundamental principles of electricity and magnetism by means of applications to those telephone and telegraph circuits and apparatus with which their work brought them into frequent contact. Since that time these notes and subsequent revisions of them have been widely used in connection with the training activities of the Long Lines Plant Department.

During the past few years too there have been issued by other units of the Bell System some very excellent texts covering electrical theory and telephone transmission problems, which have been studied to advantage in many cases by Long Lines employees.

In view of this no attempt has been made heretofore by this Department to issue a printed text of this nature but it now happens that on account of the growth in the number of Long Lines employees specializing in the more recent transmission developments affecting Long Distance service in particular, we seem justified in printing another textbook supplementing rather than supplanting the earlier texts.

Because of the magnitude of the subject covered this text is necessarily rather long, although throughout an effort has been made to treat each subject taken up as briefly as is compatible with a reasonably adequate presentation of the theory and fields of application involved. It is designed to cover all of the essential general principles of simple electrical theory, however, and to illustrate each principle presented by one or more of its outstanding applications to Long Distance telephone or telegraph practice.

The use of higher mathematics has been avoided entirely and even the more elementary branches have been used as sparingly as possible throughout the text. A general knowledge on the part of the reader of those branches of mathematics ordinarily taught in High Schools, including Algebra, Geometry, Logarithms and Trigonometry is assumed, however. In the Chapters dealing with the solution of alternating current circuits, it has also been thought desirable to take advantage of the great simplification that may be effected by the use of Vector Notation even though this may involve introducing certain simple mathematical concepts with which the reader is not familiar. For any who may have difficulty in following the derivation of equations or in solving the problems associated with the course, there is available a Mathematical Handbook which explains in the briefest

and simplest manner possible the essentials of all branches of mathematics used in the text. In some cases, it will probably be advisable for the student to review the mathematical notes concurrently with his study of this text, taking up each item as the need for it occurs. A knowledge of the more elementary principles of Physics and Mechanics is also assumed but for the benefit of any who may wish to hurriedly review these subjects, an Appendix is included giving the most important fundamental definitions and concepts.

The principal objective of the course is to acquaint the Student with the fundamental principles of electricity and of the art of electrical communication; and by means of carefully selected applications of these principles to long distance telephone and telegraph practice, to stimulate his interest in these and many other applications that he encounters in his daily work. In so far as the course achieves this primary aim, it is complete within itself, but it has an important secondary aim—it should serve as a foundation for succeeding courses which deal more intimately with the technical phases of the long distance communication art.

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"Spirit of Electricity"

# CHAPTER I

## ELEMENTARY DEFINITIONS AND OHMS LAW

### 1. Introductory

Electricity is well adapted to transmitting from one place to another and delivering in convenient form quantities of energy, either large or small. It enables the power engineer to harness the energy of an isolated waterfall and to transmit it to some distant city where it may be utilized in the form of heat, light, mechanical work, or to change the state of certain chemicals. Likewise, it enables the telephone engineer to transmit the human voice thousands of miles without loss of intelligibility. In accomplishing such feats as these it is used with precision, but we know very little of its exact nature beyond the generally accepted but not entirely complete electron theory.

According to this theory the electron is the smallest possible charge of electricity, just as an atom is the smallest possible chemical particle of any substance. Electrons are all identical and each has a definite charge and a definite "mass". By means of various ingenious methods some of which involve isolating individual electrons, these values have been carefully measured. The charge is found to be about $4.79 \times 10^{-10}$ electrostatic units and the "mass" about 1/1800 part of that of the hydrogen atom. These values are so infinitesimally small as to be almost meaningless to anyone except a trained physicist.

All substances are made up of electrons and corresponding positively charged particles known as protons. Much less is known about protons than about electrons; it has been determined, however, that they are of approximately the same size as electrons but nearly two thousand times as massive. The most widely accepted theory of the structure of the atom postulates that it is made up of a massive nucleus consisting of one or more protons surrounded by an equal number of electrons, the number and arrangement of the positive and negative particles being different for each chemical element. The simplest and lightest element, hydrogen, is made up of a nucleus consisting of a single proton around which a single electron revolves in certain fixed orbits. Heavier elements have nuclei consisting of a number of protons held together and partially neutralized by about half as many electrons and the remaining half of the electrons of the atom revolve about the nucleus in various orbits. In every case the number of electrons revolving in orbits about the nucleus gives the **atomic number** of the element and the number of protons contained in the nucleus gives the **atomic weight**. Some idea of the magnitude of the electron may be obtained by considering that its size in relation to that of the atom is comparable to the magnitude of the earth in relation to the solar system, remembering, meanwhile, that the atom itself is almost inconceivably small.

Electrons are attracted toward the atom nucleus and are repelled by one another with tremendous forces relative to their magnitude—forces infinitely greater than the gravitational forces that we are familiar with. For this reason the electrons in the atoms are for the most part held permanently in place in fixed orbits around the atom nucleus but in the atoms of many materials one or more of the electrons farthest out from the nucleus is attached rather loosely and may by various means be drawn away from the atom altogether. When this happens to a number of the atoms making up a substance, as for instance a piece of metal, it contains less than its normal quota of electrons and is said to be positively charged. At the same time something else must be negatively charged or contain more than its normal number of electrons for those taken away from the original substance must of course go somewhere. The means of bringing about such a condition are too numerous to mention, although we will consider several of them in later Chapters.

This theory explains the flow of current in a conductor as being merely a stream of electrons moving along the conductor from atom to atom in a definite direction under the influence of an outside applied force or pressure. Substances whose atoms have loosely attached outer electrons are good conductors while substances to whose atoms all electrons are tightly bound contain normally very few free electrons and are therefore poor conductors, or good insulators.

While in our study of vacuum tubes in a later Chapter we will deal with electrons as such, for most of our purposes we will not need to be familiar with all the details of the electron theory nor to know exactly what electricity is. Though we cannot observe it any more than we can actually see the force of gravity, we can observe its effect on other things about us. In this way we associate it with skilfully constructed mechanisms that are set in motion at the throw of a switch or the touch of a button, and with forms of energy that may be conveyed from place to place and changed from one state to another. We learn the conditions under which certain chemicals or work performed in a mechanical way can produce this peculiar something we call electricity, and through means of intelligently controlling it we thus employ it at will. Then, briefly, **our chief interest in electricity lies—first, in the many convenient ways in which it can be produced; second, in the means of transmitting it; and third, in the simple methods by which it may in turn produce active forces.**

In what follows, then, we will be principally concerned in the study of the more important laws of electric circuits that have been deduced from

observation and with certain of the practical applications of these laws. For a proper understanding of the electric quantities with which we will deal it is desirable that the student have a general knowledge of the more fundamental physical quantities and for the benefit of any reader who may wish to refresh his memory regarding these matters a brief review of Elementary Physics may be found in Appendix 1.

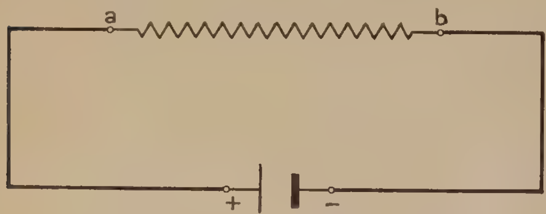



*Fig. 1—Circuit in Its Simplest Form.*

## 2. The Electrical Circuit

An electrical circuit in its simplest form consists of a source of electromotive force and a continuous path from the positive terminal to the negative terminal through a resistance. The source of electromotive force may be direct or alternating. If direct, the positive and negative terminals remain unchanged, but if alternating, their polarity is changed or reversed at frequent intervals. Accordingly, the study of electricity is divided into two parts, first, that dealing with circuits having sources of direct electromotive force commonly called **direct current circuits,** and second, that dealing with circuits having sources of alternating electromotive force commonly called **alternating current circuits.**

## 3. Electrical Pressure or Electromotive Force

Figure 1 shows a simple circuit which consists of a battery connected to a resistance and is analogous

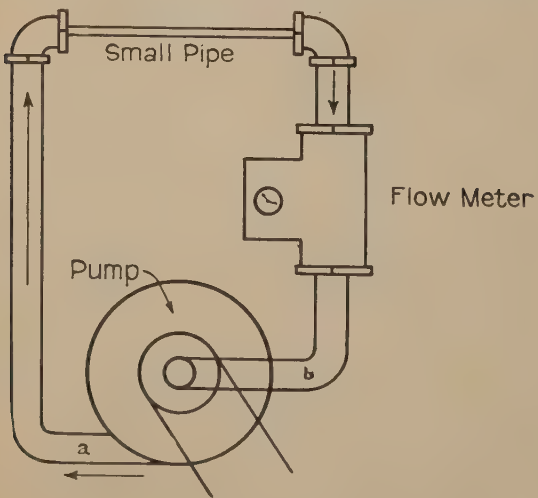



*Fig. 2—Water Analogy for Simple Circuit*

in many respects to the water circulating mechanism shown by Figure 2. In this water mechanism a pump creates a difference in pressure between the points **a** and **b.** This difference of pressure, or pressure head, will cause water to flow from the outlet pipe **a** through the small pipe to the flow meter and return to the low pressure side of the pump at **b.** The amount of water that will flow will depend upon this pressure head and upon the nature of the small pipe. The **source of electromotive force** in the simple circuit shown by Figure 1 corresponds to the **pump** and the **resistance** corresponds to the small pipe.

If a differential pressure gauge were connected between the points **a** and **b** it would register the difference in water pressure in some suitable unit such as "pounds per square inch" or "difference of head in feet". Electrical pressure, that is electromotive force or potential difference, is measured by comparing it with a unit called the volt.

## 4. Resistance

In Figure 2, if the small pipe is made longer the flow of water will be decreased although the pump maintains the constant difference in pressure between the points **a** and **b.** Also, if the small pipe is decreased in size the flow of water will likewise be decreased. Though there is no simple unit for measuring this resistance to flow of water in a pipe, it is analogous to an electrical resistance in many respects. The unit of electrical resistance is called the **ohm** and is defined as **the resistance offered to electrical flow by a column of mercury one square millimeter in cross-section and 106.3 centimeters long at a temperature of zero degrees Centigrade.**

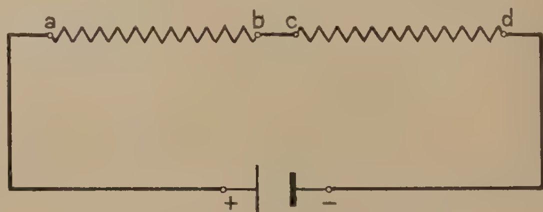



*Fig. 3—Circuit with Series Resistances*

## 5. Current

In our water circulating mechanism we can describe the **rate of flow** or current as the amount of water being circulated in gallons per second. In electrical work the current is expressed in amperes. **One ampere is that current which when passed through a solution of nitrate of silver between two silver plates under fixed conditions will cause a deposit due to electrolytic action of 0.001118 grams of silver per second.**

## 6. The Volt

The volt has been named as the unit of pressure but its size has not been defined. **A source of elec-**

tromotive force is said to have one volt of electrical pressure when it will send a current of one ampere through a resistance of 1 ohm.

## 7. Series and Parallel Circuits

A simple circuit may contain any number of resistances. Figure 3 shows such a circuit with two resistances which when connected as shown are said to be in series. Figure 4 shows another circuit with the same resistances connected in parallel. Any number may be so connected in either case.

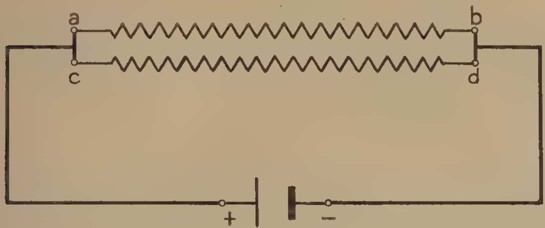



*Fig. 4—Circuit with Parallel Resistances*

The current from a battery in a parallel circuit will divide between the various resistance branches but in a series circuit, as in the flow of water in a single pipe, it cannot divide and must be identical at every point. In other words, it must have an unchanged flow through all parts of the circuit from the positive to the negative terminal.

## 8. Open Circuits

The electrical circuits shown thus far indicate no means of interrupting the flow of electricity. For the same reason that any water system should be equipped with valves or other devices for starting and stopping the flow of water, switches, push buttons, keys, etc. are used for opening and closing an electrical circuit. Figure 5 shows a circuit opened by means of a switch. Its metallic continuity is interrupted by the switch and when so interrupted there is no flow of electricity, which means that the source of electromotive force is protected against unnecessary loss of energy because no energy is being supplied when the circuit is open, or in other words, when there is no current there is no energy being taken by the circuit.

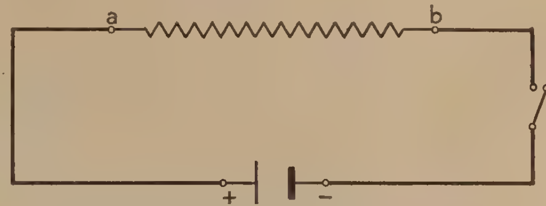



*Fig. 5—Circuit with Opening Device*

Figure 6 illustrates representative types of switches, push buttons and keys used for opening and closing electrical circuits. The familiar knife switch is a device whereby a circuit may be closed and left closed while the push button is a device whereby a circuit may be closed but must be held closed; it is a **non-locking** device. The more common designs of circuit closing apparatus used in telephone and telegraph work are called keys. When the circuit to be opened or closed does not carry an excessive current, these will perform the corresponding functions of the knife switch and the push button; that is, they may be either locking or non-locking. The locking key may be operated or closed and left closed in the same way that the knife switch may be closed and left closed, while the non-locking key must be held closed in the same way that a push button must be held closed.

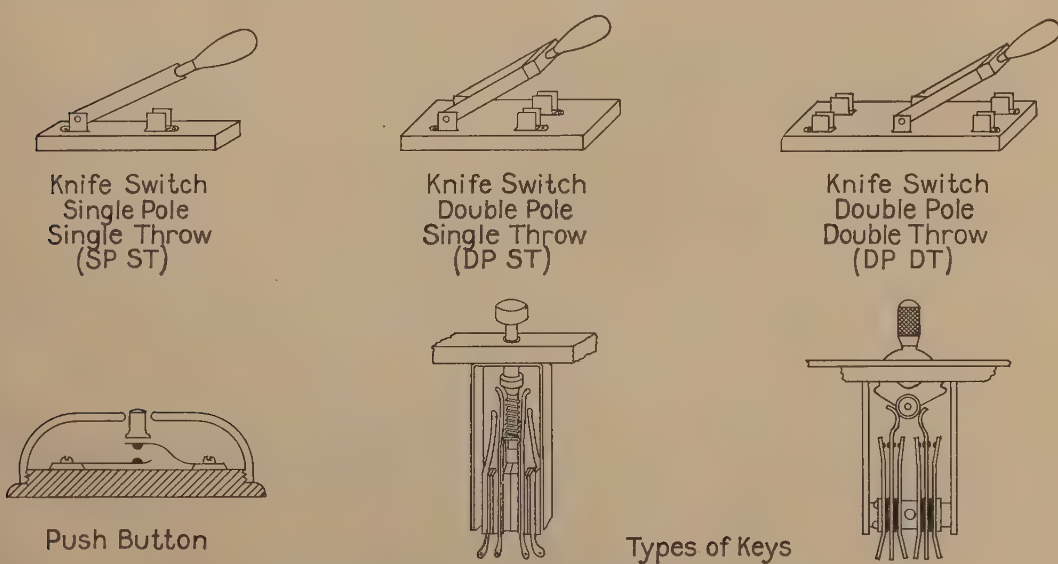



*Fig. 6—Devices for Opening and Closing Circuits*

Circuits are often opened and closed through the operation of other electrical circuits and any device for controlling one electrical circuit from the operation of another is called a **relay**.

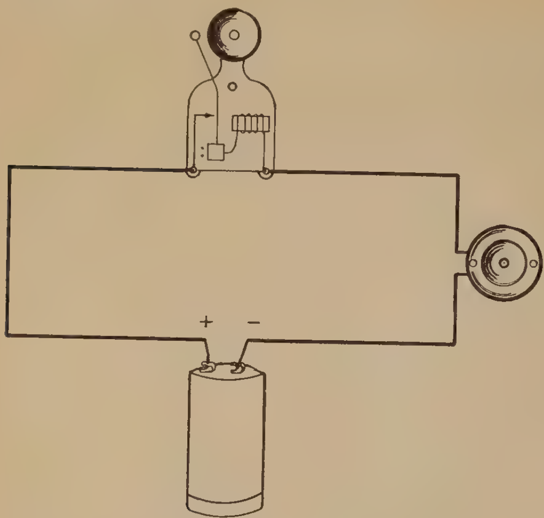



*Fig. 7—Wiring of Door-bell Circuit*

## 9. Electrical Symbols and Circuit Conventions

In the foregoing circuit diagrams we have represented the battery with a long and a short line, a resistance by a wavy line, connecting wires by straight plain lines, and connections between the wires and the battery or the wires and the resistances by small circles. These are circuit conv tions. Thus, Figure 7 illustrates an actual d bell circuit and Figure 8 shows the electrical p perties of the same circuit drawn in accorda with standard electrical conventions. There many such conventions and different ones are u for different purposes. For example, on drawi which are to guide the electrical installer when c necting wires to various units of apparatus, a sor what different set of conventions is used than drawings to illustrate a circuit's theory of ope tion. Figure 9 shows a few simple conventi that should be learned at this time.

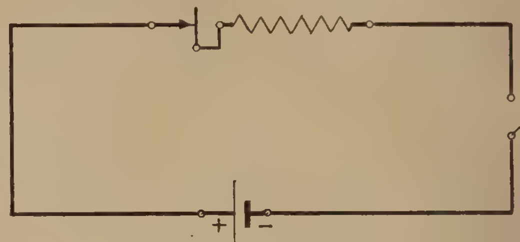



*Fig. 8—Door-bell Circuit Drawing using Conventi*

While Figure 9 shows circuit conventions u in illustrating the theory of electrical circuits diagrams, certain symbols are necessary for rep senting electrical quantities in simple mathemati formulas. Table I gives standard symbols for ectrical quantities. It is necessary to learn n those applying to the quantities we have defin The table can later be referred to for other qua ties treated.

### TABLE I

SYMBOLS USED IN ELECTRICAL WORK

| Symbol | Abbrev. | Stands for |
|---|---|---|
| I | | Intensity of current in Amperes. |
| E | E. M. F. | Electromotive force in Volts. |
| R | | Resistance in Ohms. |
| P | | Power in Watts. |
| Q | | Quantity in Coulombs. |
| V | | Reading of Voltmeter in Volts. (some special value of E) |
| A | | Reading of Ammeter in Amperes. (some special value of I) |
| C | | Conductance in Mhos (is reciprocal of R in Direct Current Work) |
| T | | Time in Seconds. |
| C | | Capacity in Farads. |
| | mf. | Microfarad (one millionth part of the farad). |
| L | H | Inductance in Henrys |
| f | | Frequency in cycles per Second. |
| B | | Susceptance in Mhos. |
| Z | | Impedance in Ohms. |
| Y | | Admittance in Mhos. |
| $\alpha$ | | Attenuation per unit length. |
| d | | Distance or length of circuit. |

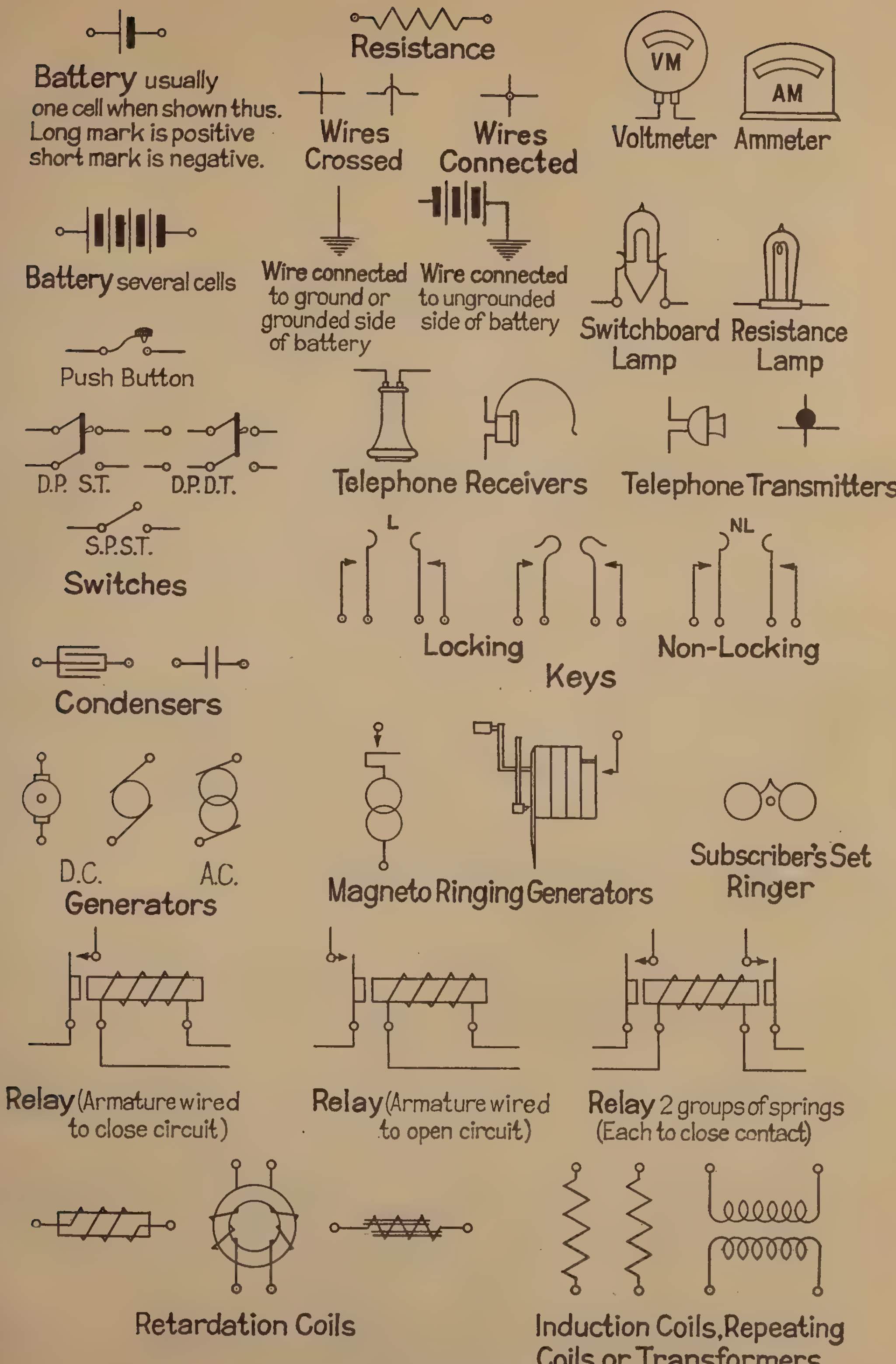



*Fig. 9—Telephone Circuit Conventions*

## 10. Ohm's Law

A German physicist named George Simon Ohm was the first to discover the relation between the electromotive force, current, and resistance of a circuit. The discovery is called "Ohm's Law" and simply expressed is—**that for any circuit or part of a circuit under consideration the current in amperes is equal to the electromotive force in volts divided by the resistance in ohms.**

This law, mathematically expressed, is as follows:

$$\text{Current} = \frac{\text{Electromotive Force}}{\text{Resistance}}$$

provided that the quantities are expressed in proper units, or

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}.$$

If in the above expression we substitute the proper symbols instead of current, electromotive force and resistance (or instead of amperes, volts and ohms) we have the following equation:

$I = E \div R$, or more commonly expressed

$$I = \frac{E}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

This is the equation for Ohm's Law. It is the most important one in all electrical work. It may be expressed in other forms but when expressed as shown permits us to calculate the current that may be expected in any circuit when we know the voltage of the source of electromotive force and when we know the resistance connected to this source in ohms.

**Example:** In Figure 10 the electromotive force of the battery is 24 volts and the resistance of the lamp connected to it is 112 ohms, what will be the value of the current flowing through the lamp?

**Solution:** $E = 24$

$R = 112$

$$I = \frac{E}{R} = \frac{24}{112} = .21 \text{ amperes, ans.}$$

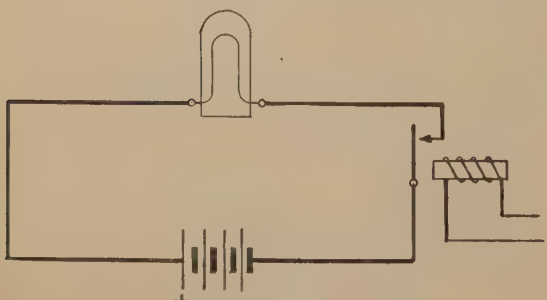



*Figure 10*

## 11. Other Ways of Expressing Ohm's Law

Equation (1) states that the current is equal to the electromotive force divided by the resistance; then by simple algebra the electromotive force must be equal to the current multiplied by the resistance, or the equation may be expressed—

$$E = R\,I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

From this equation we may find the electromotive force acting in any circuit if we know the resistance and the current.

**Example:** In Figure 8 the resistance of the door bell winding is 4 ohms. If during the instant the circuit is closed a current of .2 amperes is flowing, what is the voltage of the dry cell?

**Solution:** $R = 4$

$I = .2$

$E = R\,I = 4 \times .2 = .8$ volt, ans.

The third case is one where current and electromotive force are known and it is desired to find the resistance. Likewise Ohm's Law may be expressed for this condition. If the electromotive force is equal to the resistance multiplied by the current, the resistance must be equal to the electromotive force divided by the current or, algebraically expressed—

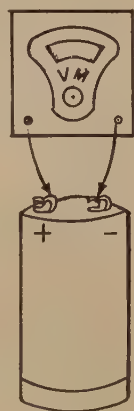



*Figure 11*

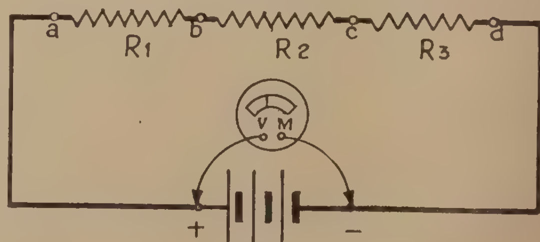



*Figure 12*

$$R = \frac{E}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

**Example:** What is the resistance connected between the points a and b in Figure 5 if the voltage of the battery is 1.3 volts and the current is ½ ampere?

**Solution:** $E = 1.3$ volts
$I = .5$ amperes

$$R = \frac{E}{I} = \frac{1.3}{.5} = 2.6 \text{ ohms, ans.}$$

## 12. Potential Differences in a Closed Circuit

We have spoken of how the differential pressure gauge may measure the difference in pressure head of the two sides of the water pump shown by Figure 2. The electrical instrument used for measuring the electrical pressure of a source of electromotive force or the potential differences between any two points in a circuit is called the **voltmeter.**

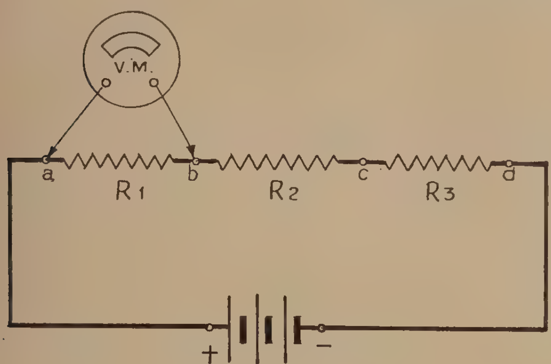



*Figure 13*

Figure 11 shows the voltmeter being used to measure the voltage of a dry cell on an open circuit. Figure 12 shows the voltmeter connected to measure the voltage of a source of electromotive force in a closed circuit. In this case we have a simple circuit with three resistances in series. If the voltmeter is connected across the points a and b as shown in Figure 13, which represents the same circuit as Figure 12, it will read a definite number of volts that is less than its reading for the battery. Likewise if the voltmeter is connected across the resistances b and c, and c and d, the three readings, that is the reading across a and b, b and c, and c and d when added together will be equal to the voltage of the battery (measured while the circuit is closed). We learn, therefore, that **the sum of the potential differences measured across all parts of the circuit, beginning at the positive pole of the battery and returning to the negative, is equal to the voltage of the battery,** or we might say, this voltage distributes itself proportionately throughout the series circuit. If in Figure 13 the value of the resistance from a to d is known, and the voltage of the electromotive force is known, it would be possible to calculate the resistance of that part of the circuit between a and b from the voltmeter reading.

**Example:** The total resistance of a series circuit is 15 ohms, the voltage of the electromotive force on closed circuit is 10 volts, the potential drop across a certain part of the circuit is 3 volts; what is the resistance of this part of the circuit?

**Solution:** For entire circuit $I = \frac{E}{R} = \frac{10}{15} = .667$ amperes

For part of circuit in question—
$E = 3$ volts.

I of series circuit is same in any part of circuit as for entire circuit, therefore, $I = .667$ amperes

$E = 3$ volts

$$R = \frac{E}{I} = \frac{3}{.667} = 4.5 \text{ ohms, ans.}$$

**The total resistance of a series circuit is equal to the sum of all the individual resistances.** In Figure 12 the total resistance is the sum of the three resistances; namely, that connected between a and b or $R_1$, that connected between b and c or $R_2$ and that connected between c and d or $R_3$:

$$R = R_1 + R_2 + R_3 \quad \dots\dots\dots\dots \quad (4)$$

**Example:** A 24-volt battery tap supplies a series circuit containing a No. 18-B resistance (40 ohms), a No. 2-N switchboard lamp (43 ohms) and the winding of a No. 118-P relay (95 ohms); what is the total resistance of the circuit and what current will flow through the switchboard lamp?

**Solution:** $R = R_1 + R_2 + R_3 = 40 + 43 + 95 = 178$ ohms, ans.

$E = 24$ volts
$R = 178$ ohms

$$I = \frac{E}{R} = \frac{24}{178} = .13 \text{ amperes, ans.}$$

## 13. Internal Resistance

If a dry cell as shown in Figure 11 is placed in a closed circuit as shown in Figure 3 and its voltage again measured with a voltmeter, a reading will be obtained which will be somewhat less than the reading for the dry cell on open circuit. This means that the electromotive force of the dry cell will depend to some extent upon the amount of current it is furnishing. As the current is increased the electromotive force is slightly decreased. This is due to a potential drop within the cell itself which is merely a drop across a resistance in the same way that the potential measured across the terminals a b in Figure 12 is a drop across a resistance, excepting that in this case the resistance is inside the dry cell. Any electrical current leaving the positive pole of the dry cell and returning to the negative pole from the external circuit must

likewise flow from the negative to the positive through the chemicals in the dry cell. These chemicals have a definite resistance called the **internal resistance.** In our consideration of the simple circuit, therefore, **we must either use the electromotive force measured on closed circuit or recognize that the open circuit electromotive force is flowing through a resistance additional to that of the external circuit.** The absolute convention, therefore, for this source of electromotive force would be that shown by Figure 14, which represents an open circuit voltage and a series resistance equal to the internal resistance.

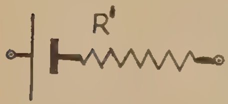


*Figure 14*

The ordinary dry cell has an internal resistance averaging about one ohm, but this greatly increases with the aging of the cell. In the telephone central office where storage batteries are used almost exclusively, the internal resistance is negligible for most direct current considerations.

### 14. Electrical Power

In the simple circuits we have thus far considered we have only dealt with resistance, electromotive force, and electrical current, but each of these circuits is actually converting energy from chemical to heat or some other form. They, therefore, have a definite power consumption or represent a definite transfer of power to some external device. We know that the scientific unit for work is the joule, equal to about ¾ths of one foot pound, and that the scientific unit for rate of doing work or for power is the watt, which is equal to about ¾ths of one foot-pound per second. The electrical units have been so derived as to facilitate convenient calculations in transforming expressions for energy from mechanical to electrical units. **In the electrical circuit if we multiply the electromotive force in volts by the current in amperes we have an expression for the power in watts.** The watt may, therefore, be defined as an electrical unit as well as a mechanical unit and is the power expended in a circuit having an electromotive force of one volt and a current of one ampere.

Because the watt is the connecting relation between mechanical units and electrical units, its value in terms of horsepower should be committed to memory,* and the following formulas should be considered second to Ohm's Law in importance.

This formula is the expression for electrical power;

$$P = EI \quad \ldots\ldots\ldots\ldots \quad (5)$$

A more convenient form for determining the power expended in any given resistance is—

$$P = RI^2 \quad \ldots\ldots\ldots\ldots \quad (6)$$

*See Appendix I.

This latter equation is apparent from Ohm's Law, which states that $E = RI$ and we may, therefore, substitute $RI$ for $E$ in equation, (5) which gives us $RI^2$.

**Example:** In Figure 12, what is the power expended in the resistance between terminals a and b if the potential difference is equal to ten volts and the resistance is five ohms?

**Solution:** $P = EI$, but $I = \frac{E}{R} = \frac{10}{5} = 2$,

then $P = EI = 10 \times 2 = 20$ watts, ans.

### 15. Quantities of Electricity

In Figure 2 we may say that the amount of water that will pass through the small pipe in a given interval of time is a definite number of gallons; thus the gallon is a unit of quantity of water. The amount of electricity that flows through an electrical conductor in one second when the current intensity (or rate of flow) is one ampere is called a **coulomb.** This is the unit for measuring quantities of electricity.

### 16. Properties of Electrical Conductors

A column of mercury was used to define the standard unit of resistance, the ohm. Other metals could have been used for this fixed standard but their dimensions would have been different from that of mercury. Dr. Ohm investigated the conducting properties of various kinds of metals and called those offering very high resistance to the flow of electricity **"poor conductors"** and those offering comparatively little resistance to the flow of electricity **"good conductors".** There is another classification for material having extremely high resistance, in fact so high as to give an open circuit for all practical purposes. These are called **"insulators".** Table II shows a few conductors in the order of conductivity. Those offering the least resistance values are at the top of the list.

Table III shows a list of materials which are commonly used as insulators. There are many other good insulators but they are not adaptable for use as such in practice.

In addition to the law showing the relation between electromotive force, current, and resistance, Ohm investigated the properties of conductors and established in addition to their relative values the following laws:

a. The resistance of any conductor varies directly with its length.

b. The resistance of any conductor varies inversely with its cross-section.

Here we have the analogy to the water pipe previously mentioned but fortunately the electrical conductors have more exact laws governing their electrical resistances than water pipes have governing their resistance to the flow of water.

## TABLE II

| RESISTANCE OF VARIOUS METAL CONDUCTORS (Compared to pure copper of same length and cross section) | |
|---|---|
| **Kind of Metal** | **Times the Resistance of Pure Copper** |
| Silver | .975 |
| Pure Copper | Unity |
| Annealed Copper | 1.032 |
| Hard Drawn Copper | 1.067 |
| Gold | 1.325 |
| Aluminum | 1.815 |
| Magnesium | 2.95 |
| Zinc | 3.76 |
| Tungsten | 4.54 |
| Brass | 5.52 |
| Tin | 6.79 |
| Iron—Commercial | 7.02 |
| Nickel | 7.54 |
| Platinum | 7.96 |
| Tantalum | 9.43 |
| Soft Steel | 10.6 |
| Lead | 12.6 |
| German Silver | 19.5 |
| Hard Steel | 29.6 |
| Mercury | 61.0 |
| Cast Iron | 64.0 |

## TABLE III

| INSULATING MATERIALS (Given in the order of their insulating properties) |
|---|
| Dry air |
| Shellac |
| Paraffin |
| Paraffin paper |
| Paraffin oil |
| Ebonite |
| Rubber |
| Porcelain |
| Sulphur |
| Glass |
| Mica |
| Silk |
| Varnish |
| Dry paper |
| Celluloid |
| Dry wood |
| Slate |
| Fiber |
| Distilled water |
| Alcohol |

## TABLE IV

ELECTRICAL PROPERTIES OF COPPER CONDUCTORS
STANDARDIZED BY LONG LINES DEPARTMENT

| Conductors | No. | Size | | Weight | Resistance | | Inductance | Capacity |
|---|---|---|---|---|---|---|---|---|
| | | Gauge | Diam. in Inches | Lbs. per Wire Mile | *Ohms per Loop Mile | Ohms per 1,000 feet | (Henrys per Loop Mile) | (Mfs. per Loop Mile) |
| Open Wire | 8 | B. W. G. | .165 | 435 | 4.02 (use 4) | .381 | .00337 | .00915 |
| | 10 | N. B. S. G. | .128 | 264 | 6.68 | .632 | .00353 | .00875 |
| | 12 | N. B. S. G. | .104 | 174 | 10.12 (use 10) | .959 | .00366 | .00837 |
| Cable | 10 | A. W. G. | .102 | 168 | 10.55 | .999 | — | — |
| | 13 | A. W. G. | .072 | 82.6 | 21.15 | 2.003 | — | — |
| | 16 | A. W. G. | .051 | 41.2 | 42.41 | 4.016 | — | — |
| | 19 | A. W. G. | .036 | 20.5 | 85.01 | 8.05 | — | — |
| | 22 | A. W. G. | .025 | 10.2 | 170.44 | 16.14 | — | — |

*These resistance values are for 20° C or 68° F; add 2/10 of 1% per degree for higher temperatures.

**Note:**—A.W.G. is American Wire Gauge and is same as B. & S. which is Brown and Sharpe Gauge

B.W.G. is Birmingham Wire Gauge and N.B. S.G. is New British Standard Gauge.

Copper is the most universally used conductor in electrical work. It offers very low resistance, does not deteriorate rapidly with age and has many mechanical advantages. There are several standard wire gauges for copper wire and three apply to the standard conductors used by the Long Lines Department.

Table IV shows the standard wire gauges used by the Long Lines Department and their resistance values. A simple rule for remembering the approximate constants for the **cable conductors** is as follows and should be committed to memory:

a. Five sizes of cable conductors are standard for the Long Lines Department and all are A. W.G. (or B and S).

b. The largest size is #10 A.W.G. Add three gauges for successive smaller sizes,—thus #10, #13, #16, #19 and #22.

c. The diameter of #10 A.W.G. is slightly greater than one-tenth inch and its resistance is slightly greater than ten ohms per loop mile.

d. Smaller sizes double resistance by the addition of each three gauges beginning with #10 as a base.

e. In cables, conductors are slightly longer than the cable lengths due to the spiraling effect. This will average about 5%.

f. Three sizes of conductors are standard for open wire 104 (#12 N.B.S.G.), 128 (#10 N.B. S.G.) and 165 (#8 B.W.G.)

g. A #10 is the nearest A.W. Gauge to #12 N. B.S.G. (104) but is slightly smaller.

# THE SOLUTION OF D. C. NETWORKS

## 17. Parallel Circuits

Figure 15 shows two resistances connected in parallel. If we apply Ohm's Law to either of these we shall find that the current in it must be equal to the potential measured across the particular resistance divided by its value in ohms, and for this particular circuit, the potential measured across either resistance is the potential of the battery. The battery is in reality supplying two currents, one through the resistance **ab** and the other through the resistance **cd.** These two currents are united and flow together in the conductors connecting the poles of the battery with the junctions of the two resistances. Likewise, for any circuit having two resistances connected in parallel, the current supplied to the combination must be greater than the current supplied to either of the resistances. If we think of the combination of resistances in Figure 15 as equivalent to a single resistance that might be substituted in their stead, we may say accordingly that the value in ohms of two resistances in parallel is less than that of either resistance taken singly.

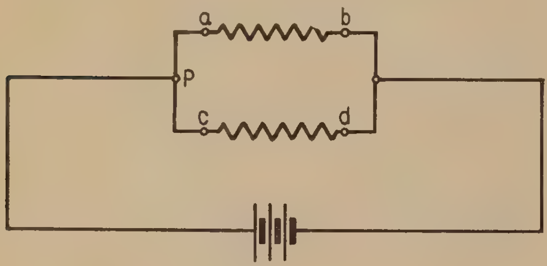



*Figure 15*

We may make calculations for determining the current flow in a parallel circuit such as is shown by Figure 15, but these are more complicated than for a simple series circuit having more than one resistance such as is shown in Figure 3. The solution of a parallel circuit is accomplished with the aid of Kirchoff's Laws in addition to Ohm's Law.

## 18. Kirchoff's First Law

Kirchoff's First Law states that at any point in a circuit there is as much current flowing to the point as there is away from it. This applies regardless of the number of branches that may be connected to the point in question. The law can be interpreted by its application to point P in Figure 15. If I is the current being supplied by the battery to the combination of the two resistances in parallel, and $I_1$ and $I_2$ are the respective currents through the two parallel resistances, then—

$$I = I_1 + I_2 \quad \ldots\ldots\ldots\ldots \quad (7)$$

If we apply Ohm's Law to the entire circuit and let R represent the value of **the combined resistances in parallel,** we have —

$$R = \frac{E}{I} \text{ or } R = \frac{E}{I_1 + I_2}$$

$$\text{But } I_1 = \frac{E}{R_1} \text{ and } I_2 = \frac{E}{R_2}$$

$$\text{Therefore, } R = \frac{E}{\frac{E}{R_1} + \frac{E}{R_2}}$$

But in this latter equation, the E's can be cancelled and the equation written —

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

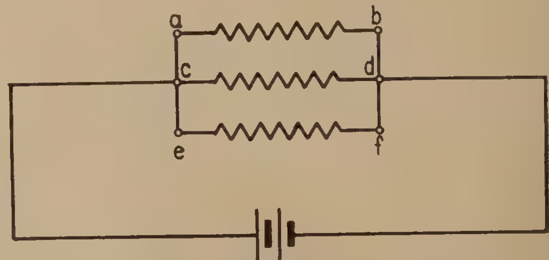



*Figure 16*

and if we simplify this compound fraction by simple algebra—

$$R = \frac{R_1R_2}{R_1 + R_2} \quad \ldots\ldots\ldots\ldots \quad (8)$$

This gives an equation for calculating the combined value of two parallel resistances. Expressed in words it may be stated as follows:

> **To obtain the combined resistance of any two resistances in parallel, divide their product by their sum.**

**Example:** What is the combined resistance of the inductive and non-inductive windings of a type B-1 relay used in a local A-board cord circuit if the inductive winding measures 16.4 ohms and the non-inductive winding measures 22 ohms?

**Solution:**

$$R = \frac{R_1R_2}{R_1 + R_2} = \frac{16.4 \times 22}{16.4 + 22} = 9.4 \text{ ohms, ans.}$$

Figure 16 shows a circuit having three resistances in parallel. A formula similar to (8) can be worked out for combinations of this kind, or calculations can be made to obtain the combined resistance of **ab** and **cd** and this value then combined with **ef**, but for problems involving more than two resistances in parallel it is usually simpler to use the conductance method.

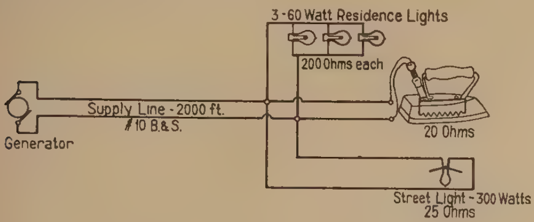



*Fig. 17—Small Power System*

### 19. Conductance

Conductance is defined in direct current work as the reciprocal of resistance. It is expressed by the symbol G, and for any single resistance—

$$G = \frac{1}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

For a combination of resistances in parallel, such as is shown by Figure 16, the conductance of the combination is equal to the sum of the individual conductances, or—

$$G = G_1 + G_2 + G_3 \quad \ldots\ldots\ldots\ldots \quad (10)$$

In a circuit having a number of resistances in parallel, it is often of advantage to solve for the total conductance of the circuit and then find its total resistance by taking the reciprocal of the total conductance.

**Example:** If a B-3 relay has an inductive winding of 16.4 ohms, a non-inductive winding of 31 ohms, and these are shunted by an 18-U resistance (of 100 ohms), what is the resistance of the combination?

**Solution:** $G_1 = \frac{1}{R_1} = \frac{1}{16.4} = .061$

$$G_2 = \frac{1}{R_2} = \frac{1}{31} = .032$$

$$G_3 = \frac{1}{R_3} = \frac{1}{100} = .010$$

$$G = G_1 + G_2 + G_3 = .061 + .032 + .010 = .103$$

$$R = \frac{1}{G} = \frac{1}{.103} = 9.7 \text{ ohms, Ans.}$$


*Figure 18*

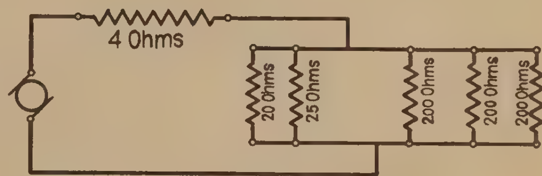



*Figure 19*

### 20. Direct Current Networks

Several resistances may be connected in such manner as to form very complicated networks. In practice many circuits are of this type. Figure 17 illustrates a 110-volt power distribution line supplying a residence and a street light. We may represent the electrical characteristics of such a circuit by the network shown by Figure 18, and can further simplify this network, as shown by Figure 19. All power supply systems are usually complicated networks of this sort.

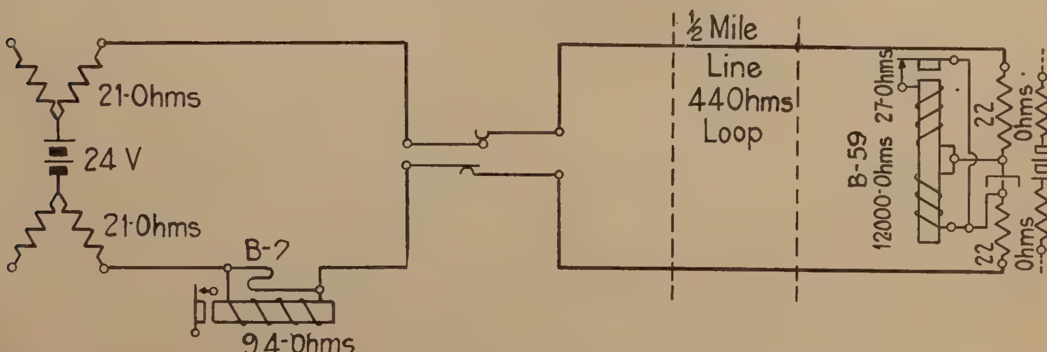



*Figure 20*

Many telephone circuits may be analyzed by drawing their equivalent network diagrams. Figure 20 represents the A-board local cord circuit connected to the local switching trunk having ½ mile of #19 gauge cable. The equivalent network is shown by Figure 21.

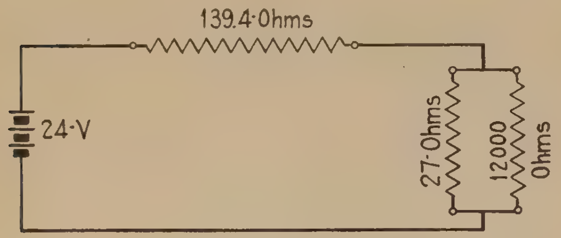



*Figure 21*

In the solution of D. C. networks, it is usually desired to know the current in the various branches, having given the resistance values of each individual branch and the voltage of the sources of E.M.F.

**Example:** What is the value of the current through each winding of the B-59 relay in Figure 20?

**Solution:** We must first find current through both windings and have — $I = \frac{E}{R}$ where E is 24 volts, and

$$R = 139.4 + \frac{R_1 R_2}{R_1 + R_2} = 139.4 + \frac{27 \times 12000}{27 + 12000}$$

$$= 139.4 + 26.9 = 166.3 \text{ ohms}$$

$$\text{Then } I = \frac{24}{166.3} = .144 \text{ amperes.}$$

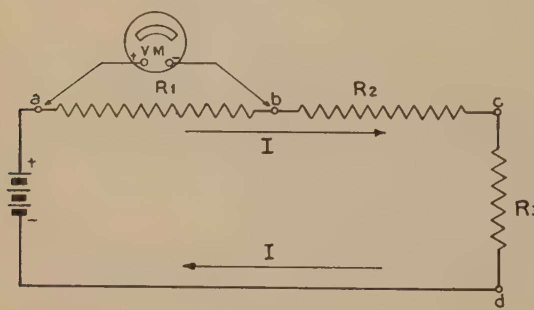



*Figure 22*

But the drop V across the two windings is the current times the combined resistance of the two windings or

$$V = I \times \frac{R_1 R_2}{R_1 + R_2}$$
$$= .144 \times 26.9$$
$$= 3.88 \text{ volts.}$$

Then applying Ohm's Law to each winding independently we have—

$$I = \frac{E}{R} \text{ and in this case}$$

$$I_1 = \frac{V}{R_1} = \frac{3.88}{27} = .1437 \text{ amperes, Ans.}$$

$$\text{and } I_2 = \frac{V}{R_2} = \frac{3.88}{12000} = .00032 \text{ amperes, Ans.}$$

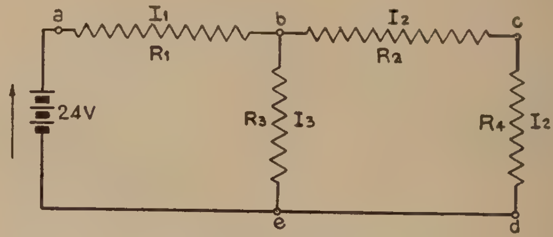



*Figure 23*

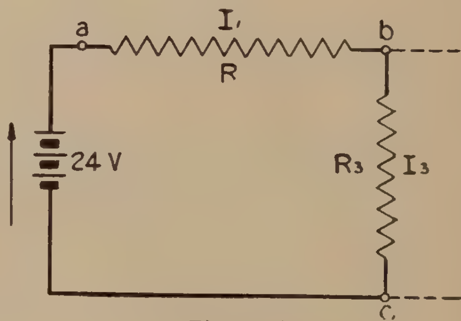



*Figure 24*

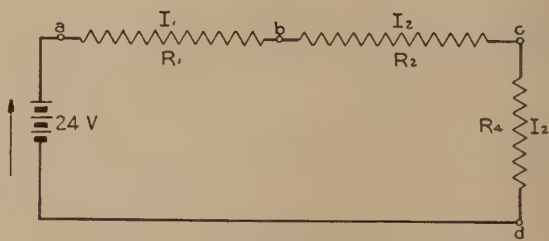



*Figure 25*

## 21. Kirchoff's Second Law

If in Figure 22 the potential drop across the resistance $R_1$ as measured by the voltmeter is represented by $V_1$ and those across $R_2$ and $R_3$ are represented by $V_2$ and $V_3$ respectively, we may write the following equation, knowing that the sum of the potential drops in any series circuit is equal to the voltage of the source of E.M.F.—

$$E = V_1 + V_2 + V_3 \quad \ldots\ldots\ldots\ldots \quad (11)$$

Kirchoff's Second Law states that if a definite direction for any closed circuit or any closed portion of a complicated circuit is assumed, the algebraic sum of the sources of E.M.F. and the potential drops is equal to zero. This, of course, requires that E.M.F.'S or potential drops in one direction be called positive and those in the other be called negative. We may for convenience accept the clockwise direction as positive, or accept as positive **all E.M.F.'S which tend to make a current flow in a clockwise direction, and as negative all potential drops due to this flow of current as well as any E.M.F.'s in the circuit tending to make current flow in the opposite direction.**

In Figure 22, Kirchoff's Second Law applied may be written as follows:

$$E - R_1I - R_2I - R_3I = 0 \quad \ldots\ldots \quad (12)$$

**Example:** Find the current values in each branch of Figure 23, if the resistance of $R_1 = 5$ ohms, $R_2 = 10$ ohms, $R_3 = 15$ ohms and $R_4 = 20$ ohms, and the voltage $E = 24$ volts.

**Solution:** Considering first only that portion of Figure 23 that is shown by Figure 24, or considering one of the two complete closed circuits, we may write, in accordance with Kirchoff's Second Law:

$$E - R_1 I_1 - R_3 I_3 = 0$$

and for that part of the circuit shown by Figure 25—

$$E - R_1 I_1 - R_2 I_2 - R_4 I_2 = 0$$

Applying Kirchoff's First Law to point b in Figure 23 we may write:

$$I_1 = I_2 + I_3$$

We thus have three independent equations containing three quantities which are unknown, namely, $I_1$, $I_2$, and $I_3$. Substituting the known values of E, $R_1$, $R_2$, $R_3$, and $R_4$ these equations may be written as follows:

$$24 - 5I_1 - 15I_3 = 0$$

$$24 - 5I_1 - 10I_2 - 20I_2 = 0$$

$$I_1 = I_2 + I_3$$

Substituting in the first equation above the value of $I_3$ from the bottom equation, viz., $I_3, = I_1 - I_2$ we have—

$$24 - 5I_1 - 15I_1 + 15I_2 = 0$$

which simplified and multiplied by two gives—

$$48 - 40I_1 + 30I_2 = 0$$

The middle equation simplified gives—

$$24 - 5I_1 - 30I_2 = 0$$

Adding these two equations we have—

$$72 - 45I_1 = 0$$

$$I_1 = \frac{72}{45} = 1.6 \text{ amperes, ans.}$$

Likewise $I_2 = \dfrac{16}{30} = .53$ amperes, ans.

and $I_3 = 1.6 - .53 = 1.07$ amperes. ans.

**22. Networks Containing More Than One Source of E.M.F.**

If a D.C. network contains more than one source of E.M.F. it may be solved by either of two distinct methods. The first of these is to solve for current values in each branch of the circuit considering only one E.M.F. at a time, and to add or subtract as the case may be, current values thus obtained for the individual branches. If we have, for example, a network such as is shown by Figure 26, containing the sources of E.M.F. $E_1$ and $E_3$, we may imagine that $E_3$ is omitted and the solution under this condition would be similar to that for Figure 23. The current values thus obtained would be those due to the E.M.F. designated as $E_1$. Those due to the E.M.F. designated $E_3$ could be solved by assuming $E_1$ short-circuited and solving the network shown by Figure 27. The values obtained for branches 1 and 3 in the two cases would be subtracted and the values for branches 2 and 4 would be added.

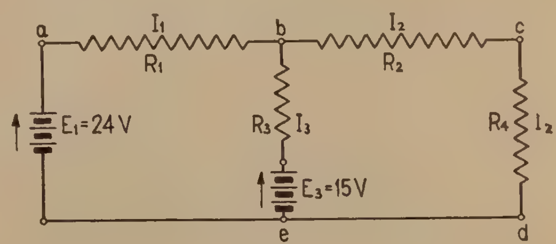



*Figure 26*

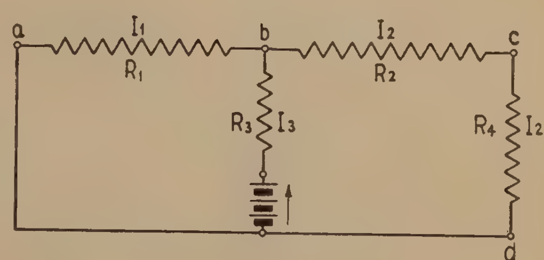



*Figure 27*

The second method is to apply Kirchoff's Laws, taking all E.M.F.'s into consideration in each equation. This is the more general method. Thus

from Figure 26 we may write, by Kirchoff's Second Law—

$$E_1 - R_1 I_1 - R_3 I_3 - E_3 = 0$$
$$E_1 - R_1 I_1 - R_2 I_2 - R_4 I_2 = 0$$
$$I_1 = I_2 + I_3$$

If the E.M.F. of the battery $E_3$ is 15 volts, we may substitute the values for the resistances and E.M.F.'s in the above equations and have the following with the three unknown current values:

$$24 - 5I_1 - 15I_3 - 15 = 0$$
$$24 - 5I_1 - 10I_2 - 20I_2 = 0$$
$$I_1 = I_2 + I_3$$

We may now solve for $I_1$, $I_2$, and $I_3$ in the same way as for Figure 23 and will have when substituting $I_3 = I_1 - I_2$ in the first equation simplified—

$$9 - 5I_1 - 15I_1 + 15I_2 = 0, \text{ or}$$
$$9 - 20I_1 + 15I_2 = 0$$

and by simplifying and dividing the middle equation by two we have—

$$12 - 2\frac{1}{2} I_1 - 15I_2 = 0$$

Adding these—

$$21 - 22\frac{1}{2} I_1 = 0$$

$$I_1 = .933 \text{ amperes, ans. etc.}$$

### 23. The Effect of Series and Shunt Resistances

It is often desired to determine the effect of a resistance either shunting some part of an electrical circuit or inserted in series in some one branch of an electrical circuit. There are formulae for calculating the change in current values due to the insertion of a resistance in a network, but these are more for convenience and are not absolutely essential. The effect of such series or shunt resistance can be determined by calculating the current values in the various branches of the electrical circuit before the additional resistances are inserted and comparing these values with those obtained by similar calculations after the insertion of the resistance.

## CHAPTER III

## MAGNETS AND MAGNETIC CIRCUITS

### 24. Nature of Magnetism

Magnetism is a peculiar property of iron, nickel and cobalt and is most pronounced in iron and certain of its alloys. Like electricity little is known of its exact nature. Our study here will be confined to those laws concerning the properties of materials learned through observation and to the behavior of these under conditions that give practical results.

The early Greeks were familiar with a natural stone that would attract bits of iron. It was a form of iron ore, now known as magnetite, and the power of attraction possessed by it was called "magnetism". It was later learned that this magnetic property could be artificially given to steel or iron by means of an electrical current.

Magnets as we know them may be classed as **permanent magnets** and **electromagnets.** A hard steel bar when magnetized becomes a **permanent** magnet since it tends to retain its magnetism under normal conditions for a long period unless subjected to heat or jarring. Soft iron tends to become easily magnetized when subject to a magnetizing influence but does not retain an appreciable part of the magnetism thus imparted to it. Consequently, **permanent magnets** are of **steel** or of such an alloy as **cobalt-steel** and cores for **electromagnets** are ordinarily made of **soft iron** or of one of the iron alloys such as **permalloy.**

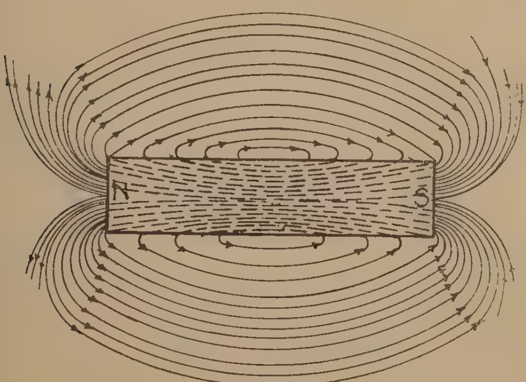



*Figure 28*

### 25. Permanent Magnets

Figure 28 represents a rectangular steel bar magnet which will attract bits of iron brought near to either end and will exert a force of either repulsion or attraction upon other magnets in its vicinity. That is, if a second magnet is placed at the end of the bar, the magnetic field will become either like that shown in Figure 29 or that shown in Figure 30. In the first case the two magnets will attract each other. In the second case they will repel each other. If they should attract and establish a combined magnetic field, such as that shown by Figure 29, merely changing ends of one magnet will give the effect in Figure 30. We then learn from the action of one magnet toward another that the two ends of any magnet are unlike. These two ends are called the **poles** and for convenience the pole having one influence is called the **north pole** and that having the opposite influence is called the **south pole.** The distinction comes from the earth, which is itself a magnet. If a bar magnet is suspended so as to swing freely, that pole which tends to point toward the north is called the north seeking or north pole; the other is called the south pole. The needle of the surveyor's compass is an application of a bar magnet free to swing on its pivot and its north pole will point to the earth's magnetic north.

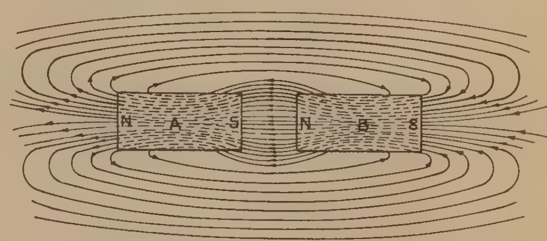



*Figure 29*

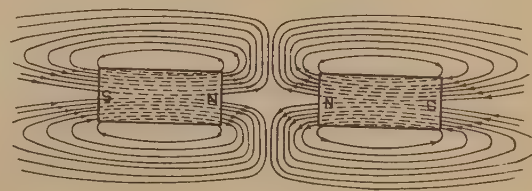



*Figure 30*

**Note:**—The north seeking pole should not be confused with the earth's magnetic pole which is near its north geographical pole; in fact, with the foregoing conventional definition of north and south magnetic poles, the earth's pole nearest the geographical north would be designated as the south magnetic pole inasmuch as it attracts unlike or north seeking poles of suspended magnets.

In Figures 28, 29, and 30 the curved lines represent magnetic lines of force which are closed loops for every magnet. Each line represents in some sense a path through which a force may act under

certain conditions. The space around or near the magnet penetrated by these lines is called the magnetic field, and the magnetic influence can be detected anywhere in this field. As an illustration Figure 31 shows the manner in which iron filings will arrange themselves when sprinkled on a sheet of glass in the vicinity of a bar magnet.


*Figure 31*

A permanent magnet may exert upon bits of iron or other magnetic materials forces either large or small, depending first, upon its magnetic strength and second, upon the location of the particles attracted with respect to the magnet's field. To express quantitatively the strength of any magnet, it follows that we must have a unit pole of definite strength with which other magnets may be compared. **If two like poles of equal strength at a distance of one centimeter apart repel each other with a force of one dyne, each is said to be a pole of unit strength or is called a unit pole.** The unit pole is very small but if we can imagine one end of a small magnet sufficiently isolated from the other end and placed in the magnetic field about the magnet in Figure 28, it will tend to move in the path of the curved line nearest it and in the direction designated by the arrow if it is a north pole, and opposite to the direction designated by the arrow if it is a south pole.

If the strength of the magnet in Figure 28 is doubled the magnetic field will, accordingly, be strengthened and may be represented by a more congested arrangement of lines of force. The force that will be exerted upon a unit pole located in a part of the magnetic field will depend upon the **intensity** of the field, or the **extent to which the lines of force at that particular point are crowded.** If the intensity is such that the force acting upon the unit pole is one dyne, the field is said to have one line of force per square centimeter or to have a field intensity of one **gauss.** In the system of electrical conventions, field intensity is expressed by the symbol "H".

In Figure 28 we see that the magnetic field has greatest intensity nearest the pole. If we should wish to create a field of greater intensity we could accomplish it by bending the magnet into the form of a horseshoe, such as that shown in Figure 32. Here each line of force emerging from the north pole returns to the south pole of the magnet through a much shorter distance than that represented by any one of the curved loops in Figure 28. If, with a unit pole or by other means, we should test the strength of the field between the two poles of a horseshoe magnet, we should find it more intense than that of a straight magnet of equal strength. We learn then that we not only shorten each line represented by a closed loop but, in so doing, create more lines. This gives us for a magnetic circuit an analogy to the electrical circuit. In the electrical circuit, if we have a long conductor connected between the positive and negative poles of a battery and decrease the resistance by decreasing its length, we increase the current strength. In the case of the magnet, if we decrease the lengths of the paths from the north to the south pole by bending the magnet into the form of a horseshoe, we increase the number of lines of force. Again, if we insert between the poles of the horseshoe magnet in the space now filled with air, a piece of soft iron, we greatly increase the number of lines of force existing in the circuit formed by the magnet itself and the soft iron used for closing this circuit between the north and south poles. This is analogous to decreasing the resistance of an electrical circuit by substituting a conductor of lower resistance for one of higher resistance.

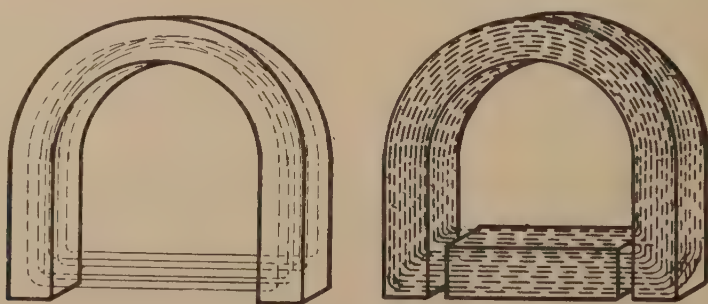


*Figure 32*

**Note:**—While the force one magnet exerts upon another depends upon the nature of the resultant fields, there is an approximate law which states that the force of attraction or repulsion varies inversely as the square of the distance separating the poles in question and directly as the strength of the magnets. Expressed as an equation this law may be written—

$$f = \frac{m_1 \; m_2}{d^2}$$

Here f is in dynes, d in centimeters and $m_1$ and $m_2$ are the strengths of the magnets in unit poles.

## 26. The Magnetic Circuit

In a magnetic circuit the lines of force as a group are called the **flux.** In any part of the circuit, either inside the magnet or in the medium used to close the circuit, as well as in any part of the surrounding air, the number of lines of force per square centimeter is called the flux density for that particular point and this is represented by the symbol B. It follows from the foregoing discussion of lines of force being increased by the insertion of materials other than air in the magnetic field, that the flux density will depend upon the materials of the completed magnetic circuit and the strength of the magnet, in the same sense that the current strength in any given cross section of conductor will depend upon the **resistance** of the closed electrical circuit and the **electromotive force** applied. We may then consider that there is a property of the closed magnetic circuit which is analogous to the resistance of a closed electrical circuit. This property is called **reluctance.** And, likewise, there is a property of the magnet which is analogous to the electromotive force of a battery. This is called the **magnetomotive force.** For the complete magnetic circuit we may apply an equation analogous in every respect to Ohm's Law which, in words, may be stated—**the flux for any given magnetic circuit is equal to the magnetomotive force of the magnet divided by the reluctance of the closed circuit.** The above law expressed mathematically may be written

$$\phi = \frac{M}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

where the symbol for flux is "$\phi$", for magnetomotive force is "M" and for reluctance is $R$

$$\text{or } \textbf{Lines of force} = \frac{\text{gilberts}}{\text{oersteds}}$$

Equation (13) is analogous to Ohm's Law as expressed by equation (1)

$$I = \frac{E}{R}$$

$$\text{or} \qquad \text{Amperes} = \frac{\text{volts}}{\text{ohms}}$$

In practice the above magnetic equation is seldom used in the form shown but from this relation we derive other equations dealing with flux density, field intensity and magnetic properties of iron. These will be treated along with a discussion of electromagnets from which we shall learn more of the terms "magnetomotive force" and "reluctance" as well as their respective units.

While we may see that in many respects the magnetic circuit is analogous to the electrical circuit, it is well to remember that the analogy is not complete since there are other respects in which the two circuits differ. The two more important of these to bear in mind are as follows:

(a) A magnetic circuit can never be entirely opened; a magnetic field must exist at all times in the vicinity of a magnet. For this reason the magnetic circuit would be more nearly analogous to the electrical circuit submerged in water. When the continuity of the metal conductors forming such an electrical circuit was broken, the circuit would be completed through the liquid across its gap. Though the current strength might be decreased in this way, the circuit could never be entirely opened; neither would the current flow be limited to the submerged metal conductors. There would be other flow surrounding the conductors but not of such great intensity as inside the metal conductors.

(b) Flux is not analogous to current since current is a rate of flow of electricity while the nature of flux is more nearly a "state" or "condition" of the medium in which it is established.

## CHAPTER IV

## MAGNETS AND MAGNETIC CIRCUITS

(Continued)

### 27. Electromagnets

If a straight vertical conductor carrying an electrical current pierces a cardboard as shown in Figure 33, there may be detected on the plane of the cardboard a magnetic field with lines of force encircling the conductor. To illustrate further, if iron filings are sprinkled on the cardboard they will form visible concentric circles as shown by Figure 34. Through such observations as these we learn that **wherever an electrical current is flowing there is an established magnetic field and the loops formed by the encircling lines of force are always in a plane perpendicular to the electrical conductor.**

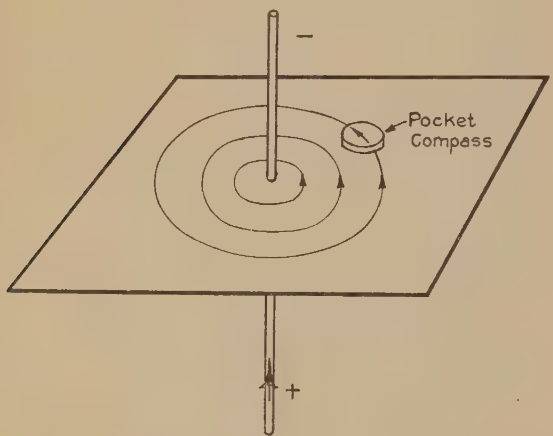


*Figure 33*

If in either Figure 33 or 34 a small pocket compass is placed near the conductor, the needle will align itself tangent to some one of the many concentric circles. If the compass is moved slowly around the wire, the needle will revolve on its pivot and maintain its tangential relation. It will also be found that the direction of the lines of force with respect to the direction of current flow is that represented by the arrows in Figure 33.

Though this magnetic effect is a positive one, under the conditions shown in the figures and even with a very strong current flowing in the conductor the magnetic field represented by the concentric circles is relatively weak. But if the electrical conductor is made to form a loop, the groups of lines of force forming concentric circles for every unit of the conductor's length can be imagined as arranging themselves as shown in Figure 35. The closed loops are no longer concentric. They become more crowded in the space inside the loop of wire and less crowded in the space outside the loop of wire. Accordingly, the intensity of the magnetic field about any conductor may be increased. Let us consider the single line of force which Figure 36 shows enclosed by imaginary boundaries to the space it occupies both within and without the loop of wire. We may express the intensity in terms of the cross-section of this imaginary space. At the point "p" inside of the loop the intensity is

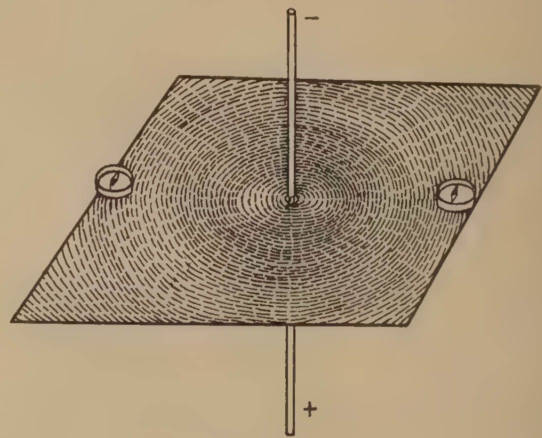


*Figure 34*

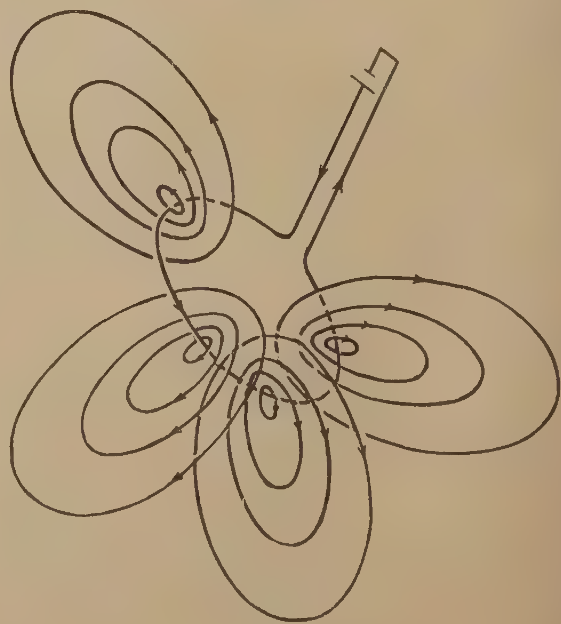


*Figure 35*

such as to give one line of force for the area represented by the cross-section "a", and at the point "P" outside of the loop the intensity is such as to give one line of force for an area represented by "A". It follows that we may express **field intensity** in terms of **lines of force divided by a cross-sectional area.**

The adopted unit for field intensity is one line of force per square centimeter and the name of this unit is the "gauss". We may write therefore

$$H = \frac{\phi}{a} \qquad (14)$$

or, the intensity in gausses is equal to the number of lines of force divided by the area in square centimeters.

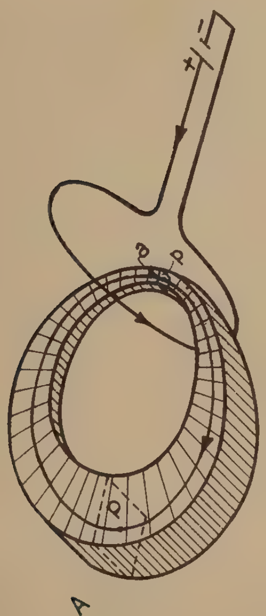



*Figure 36*

If, instead of having an electrical circuit consisting of one loop of wire, we have a circuit consisting of several turns of wire such as the winding on the spool shown in Figure 37, the intensity of the field is multiplied by the number of turns of wire. Thus, the value of "H" at any point for two turns would be twice that for a single loop; for three turns, three times that for a single loop, and for "n" turns, "n" times that for a single loop, providing the turns are sufficiently close together so that the leakage between successive turns is negligible.

Comparing Figure 37 with Figure 28, we find that the current flowing through the coil of wire creates a magnetic field similar to that of a bar magnet.

In Figure 33 the relation between direction of current flow and direction of lines of force was shown by arrows. We use this same relation in Figure 35 and going one step farther we may determine the north and south poles of the magnet formed by the coils shown in Figure 37. A simple way to remember the relation for any electrical winding is the right-hand screw relation illustrated by Figure 38. Here if we assume current flowing through a winding in the direction of "turn" for the right-hand screw, the lines of force leave the point of the screw which is the north pole and enter the slot which is the south pole.

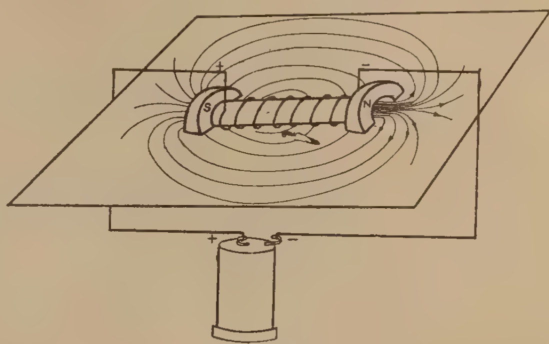



*Figure 37*

In Figure 32 the number of lines of force in the magnetic circuit established by the horseshoe magnet was greatly increased by the insertion of a piece of soft iron between the north and south poles. Likewise, if in Figure 37 the spool shown has a soft iron core, the density of the lines of force will be greatly increased. Further, if the core of the winding is bent in the shape of a horseshoe as shown in Figure 39, we have the customary electromagnet which is capable of exerting considerable force.

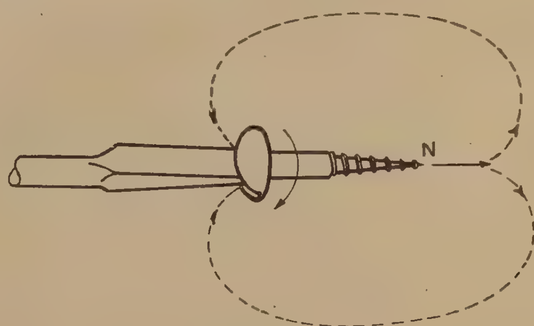



*Figure 38*

## 28. Relation Between Current and Field Intensity

If we increase the current strength in the winding shown by Figure 37, we will find that the intensity of the magnetic field within the coil is increased proportionately. Thus, the value of "H"

or the magnetic field intensity in air is directly proportional to the current flowing in the winding. We may then for some given condition establish a definite relation between field intensity and electrical current.

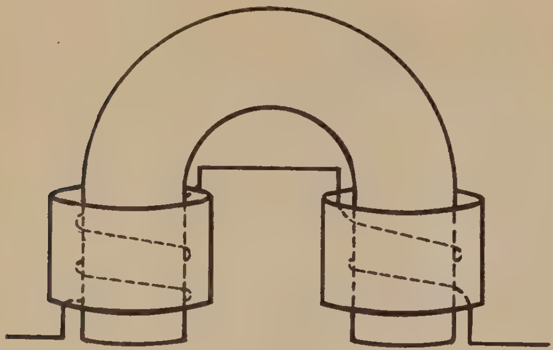


*Figure 39*

A winding such as that shown in Figure 37 is called a **"solenoid"** and if such a solenoid is very long and is constructed with one turn of wire to each centimeter of length and the current carried by it is one ampere, the field intensity in the air on the inside of the solenoid is equal to .4 x 3.1416 or 1.26 gausses. Since a gauss is defined as one line of force per square centimeter of cross-section, this means that one ampere of current will give 1.26 lines of force per square centimeter cross-section inside the solenoid. The field intensity inside any solenoid would then be expressed by the following equation:

$$H = 1.26 \frac{nI}{1} \qquad (15)$$

where "n" is the total number of turns of the solenoid, "I" is the current in amperes and "1" is the length of the solenoid in centimeters. This equation is apparent since one turn of wire per centimeter for a current of one ampere gives 1.26 gausses and the intensity is increased proportionally to the current and to the number of turns of wire per centimeter of length.

In electrical practice, the term "ampere turn" is frequently used which merely means the product of "n" and "I" in equation 15.

In order to produce a field intensity "H" inside the solenoid a certain magnetizing force is of course required, and it is convenient to think of this as the magnetizing force per centimeter length of the solenoid because in air its value is identical with the value of "H" in the system of units used. We may then express the total magnetizing force of the solenoid or its magnetomotive force as the field intensity (or magnetizing force per centimeter length) in gausses times the length of the solenoid in centimeters—thus:

$$M = H \times 1 = 1.26 \text{ NI} \qquad (16)$$

While considering "M" as a magnetic pressure in every way analogous to "E", we have defined no definite term in the electrical circuit strictly analogous to "H" but such a quantity may be imagined as "the distributed 'E' in the form of voltage drop per unit length of uniform conductor, or that element of the electromotive force tending to force a current through each unit length of conductor."

In the magnetic circuit the magnetomotive force for the complete coil and the reluctance of a complete magnetic circuit are not the most convenient quantities for practical calculations. The magnetic circuit though analogous in many respects to the electrical circuit, does not take a definite form. The lines of force may not be distributed equally throughout the cross-section of the circuit like the current flow throughout the cross-section of a conductor. There is always present the surrounding air which is an electrical insulator but is not a magnetic insulator. We, therefore, use another equation more frequently than equation (13), which is likewise in the form of Ohm's Law and analogous to it, but is expressed in the terms of quantities **per unit** of magnetic circuit rather than for the complete magnetic circuit.

## 29. Flux Density, Field Intensity and Permeability

In discussing "field intensity" we have considered it as a force existing only in air and defined it in terms of "lines of force per square centimeter". On the other hand, we have seen that if iron is inserted in a solenoid such as that shown by Figure 37, the lines of force will be greatly increased. **This means that the flux density or lines of force per square centimeter of cross-section** inside the solenoid is much greater than that defined as the field intensity. In inserting the iron we have greatly lowered the reluctance of the magnetic circuit. In lowering the reluctance, the magnetomotive force has established a greatly increased flux. We then learn that if iron is introduced into the magnetic circuit, density will depend upon the strength of the field in the air before the iron is inserted, and upon certain magnetic properties of the iron or the adaptability of the iron for lowering the reluctance per unit of length.

As noted above we may think of the field intensity "H" in air in the sense of a definite **magnetizing force** which will set up a greatly increased flux in any unit length of iron having a lower reluctance than air. Ordinarily we do not use the **reluctance of iron per unit length** under given circuit conditions but use instead a term which is the reciprocal of reluctance or is analogous to conductance per unit length of circuit for a conductor in the electrical circuit. This property of iron is known as permeability and is represented by $\mu$. With this quantity we may express the flux per unit cross-section in the form of an equation:

$$\frac{\phi}{A} = H \times \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

$$\text{or} \quad B = H \times \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

where B is the conventional symbol for lines of force per centimeter cross-section and is called the **flux density.**

This equation may be written in other forms:

$$\mu = \frac{B}{H} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

$$\text{or} \quad H = \frac{B}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

## 30. Magnetic Properties of Iron

Permeability has been compared to conductance per unit length of conductor or to **electric conductivity.** There is one distinction, however, which is most essential. The stability of the iron under various degrees of magnetization is not equal to that of the ordinary metallic electrical conductor. In the electrical circuit the resistance or conductivity remains very nearly fixed for any degree of current strength unless there is some change in temperature. While the same may be said of the magnetic circuit in air, in iron the condition is different. As the number of lines of force are in-

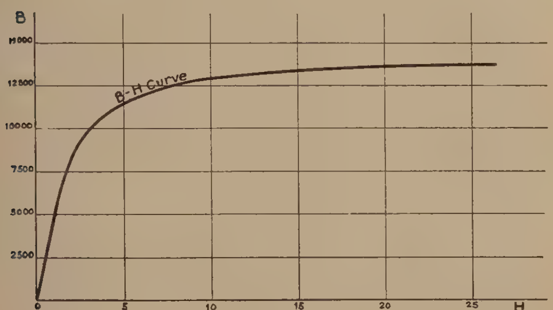



*Figure 40*

creased (or the flux density is increased), the permeability of the iron is changed and any further increase in the magnetizing force (or field intensity) may not mean a proportional increase in the flux density. In simpler terms, that property of the iron which enables it to establish more lines of force depends entirely upon the number of lines of force that it already has. After a certain number per square centimeter of cross-section, or a certain flux density, the iron becomes less effective and regardless of any further increase in field intensity, the flux density may have already become so great that **additional** lines of force cannot be established any more readily than if the core were of air. This condition is called the "**saturation point**" of the iron.

## 31. B-H Curves

Table II shows the resistance of electrical conductors compared with copper. A similar table could be compiled for electrical conductivity by taking the reciprocal of the resistance values shown. Such a table would be analogous to a magnetic table for permeability; but to give, accurately, the permeability for various kinds of iron, it is necessary to show a complete curve rather than a single tabulated value. Such a curve is illustrated by Figure 40 which is taken for a magnetic iron used very generally by the Western Electric Company in the manufacture of relays and other telephone apparatus. The curve was determined after the iron had been annealed for three hours at a temperature of 900° C. Every kind of iron has some such curve. A magnetization curve will ordinarily depend upon many things, such as

(a) Whether cast iron, wrought iron, steel or an alloy of these.

(b) Degree of purity.

(c) Previous magnetic history; that is, whether or not it has been subject to a high degree of magnetization in the past.

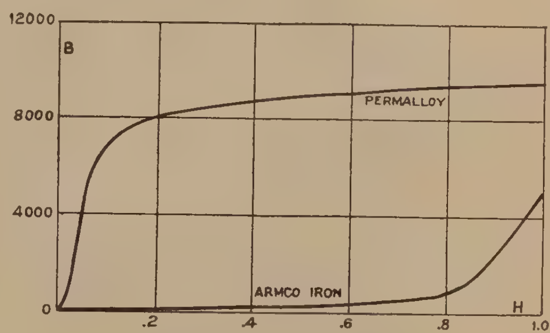



*Figure 41*

At low values of field intensity, ("H" below one gauss) the new magnetic material, permalloy, which is an alloy of nickel and iron has a very much higher permeability than iron, making it extremely useful in communication work where low values of field intensity are common. Figure 41 gives B-H curves for permalloy and for a standard iron for low values of "H" and it may be noted from this that the magnetic flux for a given magnetizing force is very much greater in the permalloy than in the iron over the range covered.

## 32. Hysteresis Loop

If a piece of iron is subjected to an increasing magnetizing force until the saturation point is reached and then the magnetizing force is decreased to zero and established in the opposite direction until the saturation point is again reached, and if the magnetizing force is again decreased to zero and again increased until the cycle is completed,

the relations between flux density and field intensity for all parts of the cycle may be represented by a curve such as one of those shown by Figure 42 which is called the "**hysteresis loop**". Here it is seen that after the iron has once reached the saturation point it does not return to its original magnetic condition no matter to what magnetizing forces it may be subjected. For example, an inspection of the hysteresis loop shows that iron will retain a certain degree of magnetization after the magnetizing influence has been reduced to zero. This is particularly true of hard steel and is the reason that all permanent magnets are made of hard steel. The two curves of Figure 42 illustrate the difference in the hysteresis loops of hard steel and soft iron. The fact that soft iron has a narrow hysteresis loop makes it adaptable for the cores of electromagnets. We may note here, however, that the hysteresis loop for permalloy is very much narrower than that for soft iron at low values of magnetizing force. This is illustrated in Figure 43 where the hysteresis loop for permalloy is compared with a standard iron.

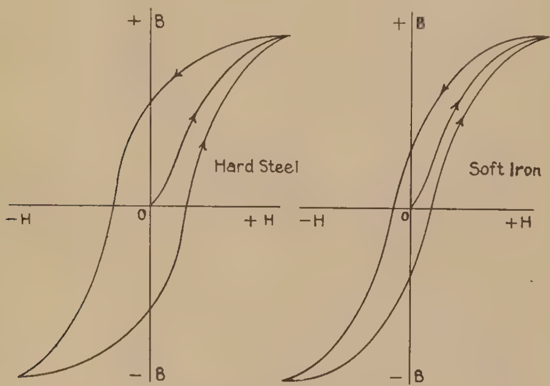



*Fig. 42—Hysteresis Loop.*

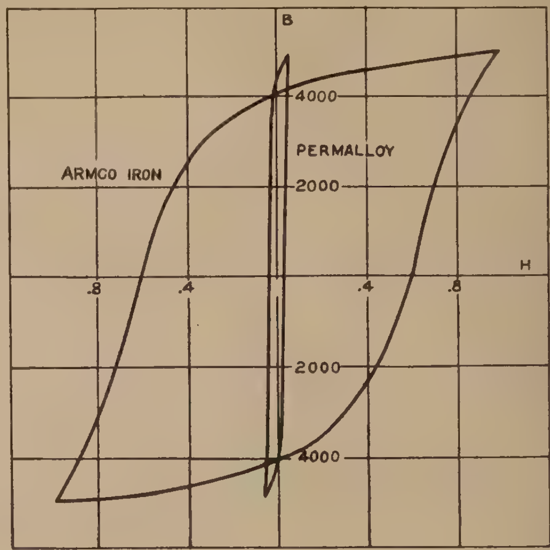



*Figure 43*

## CHAPTER V

## ELECTRICAL MEASUREMENTS FOR DIRECT CURRENT CIRCUITS

### 33. The Measuring Instruments

We have been discussing such electrical quantities as the volt, the ampere, the ohm and the watt, but little has been said about the electrical instruments that are used to measure these quantities. The group of instruments which we may call the more commonly used ones includes the galvanometer, the voltmeter, the ammeter, the Wheatstone bridge (including a galvanometer) the megger, and the wattmeter. At this stage of our study it is important that we learn the fundamental principles of these measuring instruments and the distinction between instruments designed for different purposes, but it is not important that we study long descriptions of their construction or those details of design pertaining only to their manufacture. They are ordinarily sealed at the factory and are seldom repaired by the local equipment man. Let us, therefore, concern ourselves with an intelligent and skillful use of them and only with those principles of their operation that are essential for this.

The galvanometer may be considered the most elementary of electrical measuring instruments in that it is nothing more than a sensitive device for detecting electrical (direct) currents. It is not designed to determine magnitudes of currents but merely their presence. Naturally its effectiveness in detecting currents of extremely small values depends upon its sensitiveness and while the galvanometer is the simplest of the group of instruments used in daily practice, we may consider it one of the most delicate. It ordinarily consists of a coil of several turns of very fine wire suspended between the poles of a permanent horseshoe magnet and held in a neutral position by the torsion of delicate suspension fibres or other equally delicate means. The suspended coil carries a light needle which stands at the center of a fixed scale when the suspended coil is held in its neutral position with respect to the permanent magnet. A very small current when flowing through the suspended coil will set up a magnetic field that will tend to allign itself with the field of the permanent magnet and thereby cause a deflection of the needle from its neutral position on the fixed scale.

The voltmeter (of the revolving coil type) is a galvanometer more ruggedly designed, having an extremely high resistance and with the scale so calibrated as to read the potential impressed on the terminals of the instrument. Of course, the voltmeter deflection is caused by a very small **current** flowing through the high resistance winding, but in most simple circuits, due to the extremely high resistance of the voltmeter winding, this electrical current is negligible compared with the much greater current values in the various circuit branches. The instrument is considered, therefore, as measuring potential differences between any points in a simple circuit where its terminals may be connected rather than as measuring any small current values that may flow through its winding due to these potential differences. Unlike the galvanometer which is used merely to detect the presence of current, the voltmeter must have its terminals designated as positive and negative (unless it is a **"zero center scale"** type). We have already illustrated the use of this instrument in determining the E.M.F. of a battery or drop in E.M.F. between any two points in a series circuit.

The ammeter is likewise an application of the galvanometer principle, likewise usually more rugged in design, and likewise has a calibrated scale. But in this case the scale is calibrated to measure the value of the current that flows through its winding, instead of the electromotive force across its terminals. We recall that in Figure 2 a flowmeter determined the gallons-of-water-per-minute being pumped through a water circuit. The ammeter is analogous to this flowmeter. It is inserted directly in the path of the current and the entire flow goes through the instrument (or in some cases through a calibrated shunt for the instrument). For the same reason that a water flowmeter should not be so constructed as to retard appreciably the flow of the water by causing a drop in head, **the ammeter must, unlike the voltmeter, have a very low resistance.** We may, therefore, think of the ammeter as a "flowmeter" designed with very low resistance so that it will not cause an appreciable readjustment of current or voltage values in any network when it is inserted to determine the current flow in any one branch.

Later we are to discuss the precautions to be taken in the use of instruments but just here it might be stated that wherever the ammeter is used there should be a consciousness that Ohm's Law is never failing in that it applies to every circuit branch, and that the current which will flow through the ammeter will be very large if an appreciable potential is connected across its terminals without other resistance in the circuit. As an illustration, if an ammeter has an internal resistance of .005 ohms and an electromotive force of one volt is connected to its terminals, the current that will flow through it in accordance with Ohm's Law will be approximately 200 amperes. This may be considerably in excess of the maximum current value for which the instrument is designed. It is well to remember, therefore, that the ammeter is an instrument that **will cause a short circuit** when connected across points in a circuit having a considerable difference in potential, while the voltmeter is on the other hand for most practical purposes **an open circuit** and unless connected to points having potentials higher than its greatest scale reading, it is not

likely to be damaged from excess current values. In the language of the electrician, the **ammeter must always be inserted and never connected across.**

Voltmeters and ammeters are manufactured for different ranges of voltage and current values and one instrument often has several scales. Instruments for measuring small values are prefixed with milli meaning one thousandth or micro meaning one millionth. Thus, we have milliammeter, millivoltmeter, etc. It is obvious that an **instrument must not be used when the value of the E.M.F. or current to be measured is likely to be greater than the maximum scale reading.**

If a voltmeter measures at any given instant the E.M.F. across any electrical circuit (either branch or mains) and an ammeter at the same instant measures the current in the same circuit (either branch or mains) the product of the two readings is from the formula $P = EI$ equal to the power in watts supplied to the circuit. Meters are designed with both ammeter and voltmeter terminals which read directly this product or the power in **watts.** These are called wattmeters.

There are two remaining instruments in the commonly used group. These are the Wheatstone bridge and the megger. The Wheatstone bridge is simply a network of resistances which can be used in connection with the galvanometer for measuring an unknown electrical resistance by an accurate comparison method. The megger is a combination of a magneto source of electromotive force and a sensitive meter calibrated to read values of very high resistances connected across its terminals. A more detailed description and the practical use of these instruments will be discussed along with the various methods of measuring resistance.

### 34. Measurements of Resistance—Methods Used

There are numerous methods for measuring electrical resistance and the one which is most practical depends upon—

(a) the magnitude of the resistance to be measured

(b) the conditions under which it is to be measured

(c) the degree of accuracy required

Probably the most difficult resistance measurements are those of extremely low values. Examples of these are: the internal resistance of an ammeter (or the resistance of an ammeter shunt); the resistance of an electrical connection such as the connection between cells of a storage battery; the resistance of an electrical bond, such as bonds used to prevent electrolysis and connected between railroad rails and water pipes or from one railroad rail to another. Where very low resistances are to be measured accurately, it is usually a complicated laboratory process. Fortunately, we have but few such cases in our work, though there are cases where the presence of low resistance values is to be determined but not necessarily with a great degree of accuracy. For example, in the case of a connection between the cells of a storage battery we may desire to know whether the resistance of the connection is greater than it should be. Were this to be accurately measured, the measurement would be a difficult one to make but it can usually be determined for practical purposes by some simple test such as touching the two sides of the connections with the terminals of a telephone receiver and listening for a click due to the potential drop caused by the resistance. It follows that we may discuss preferably and in particular the practical methods used for measuring either those resistance values which are appreciable, such as the ones that are important in simple circuits, or those resistance values which are extremely high, such as the insulation of open wires or cable conductors.

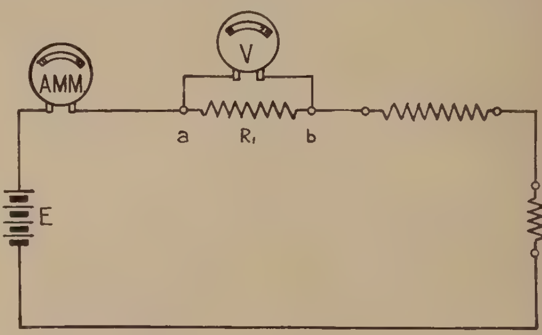



*Fig. 44—Resistance Measurement by Voltmeter—Ammeter Method.*

### 35. Voltmeter—Ammeter Method

Figure 44 shows a simple series circuit. Let us assume that it is desired to determine the value of the resistance $R_1$. We have learned that if a voltmeter is connected across the terminals a and b as shown, it will measure the potential drop across the resistance. But if, at the same instant this reading is taken, an ammeter is so inserted as to read the value of the current flowing through the

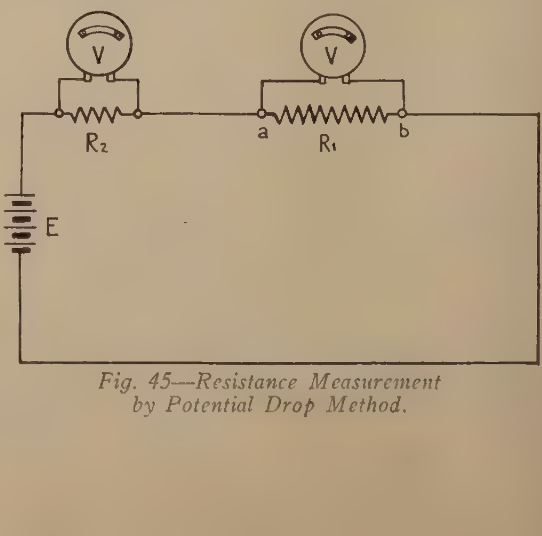



*Fig. 45—Resistance Measurement by Potential Drop Method.*

resistance $R_1$, we will have not only an E.M.F. reading but a current reading as well and from the two, the value of the resistance may be calculated by Ohm's Law. Ohm's Law states $R = E/I$, and for this particular resistance $R_1 = V_1/I_1$.

Example:—In Figure 44 voltmeter reading is 5 volts, ammeter reading is .5 ampere, what is value of resistance $R_1$?

$$R_1 = \frac{V_1}{I_1} = \frac{5}{.5} = 10 \text{ ohms, ans.}$$

### 36. Drop in Potential Method

If in Figure 45 it is desired to determine the value of the resistance $R_1$, the drop in potential method can be used if a second resistance $R_2$ of known value is inserted in series and the voltage drops across both $R_1$ and $R_2$ are measured. Since the two resistances are directly in series, the same current is flowing through both and from Ohm's Law:

$$I = \frac{V_1}{R_1}, \text{ and also } I = \frac{V_2}{R_2}$$

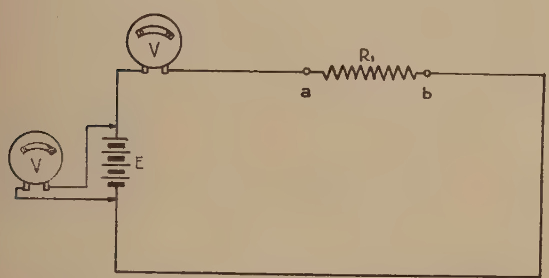



*Fig. 46—Theory of Insulation Measurement.*

$$\text{Therefore, } \frac{V_1}{R_1} = \frac{V_2}{R_2}$$

which may be written either

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

$$\text{or} \quad R_1 = R_2 \frac{V_1}{V_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Example: If in Figure 45 the value of $R_2$ is 10 ohms and the drop across it is 12 volts, what is the value of $R_1$ which has a drop of 8 volts?

Solution:

$$R_1 = R_2 \frac{V_1}{V_2} = 10 \times 8/12 = 6.67 \text{ ohms, ans.}$$

### 37. Insulation Measurements

The application of the drop of potential method which has greatest importance in telephone and telegraph work is its special adaptation to insulation measurements.

If the series circuit in Figure 45 contains no resistance other than $R_1$ and $R_2$ it is not necessary to measure the drop across $R_1$ because it will be equal to the potential of the battery minus the drop across $R_2$. The formula for this special case may be written.

$$R_1 = R_2 \frac{E - V_2}{V_2} \quad \ldots\ldots\ldots\ldots\ldots (22)$$

when E is the potential of the battery.

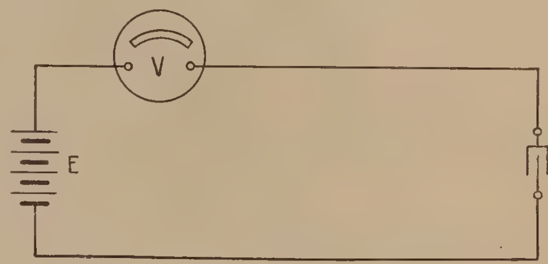



*Figure 47*

If $R_1$ is very high in value such as a "leak" due to poor insulation, it can be measured using formula 22 but instead of using a second known resistance, the **voltmeter itself** may be inserted in series with the battery and $R_1$ as shown in Figure 46. The reading $V_2$ then applies to the drop across the **voltmeter's own resistance** which, as has been previously stated, is very high. But since the resistance being measured is very high this gives greater accuracy than if a known resistance $R_2$ having a lower value were inserted and a drop of lower value measured across it. In fact, voltmeters used for measuring insulation are especially designed to have abnormally high internal resistance. The ones used in the Number 4 and 5 Testboard standard testing circuits have a resistance of 100,000 ohms.

Figure 47 shows the drop of potential method with series voltmeter for measuring the insulation of a condenser.

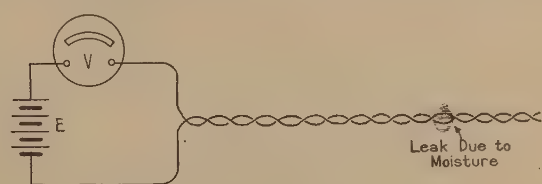



*Figure 48—Metallic Insulation Test.*

Figure 48 shows a "leak" between two cable conductors and Figure 49 a "leak" between an open wire and the ground, both being measured in the same manner.

For this application Formula 22 is ordinarily written—

$$X = r\,\frac{E-V}{V} \text{ or}$$

$$X = r\left(\frac{E}{V} - 1\right) \quad \ldots\ldots\ldots\ldots\ (23)$$

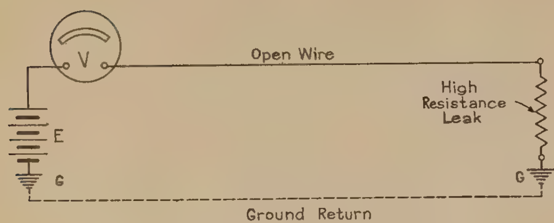



*Fig. 49—Test for Insulation to Ground.*

where X is the unknown insulation resistance **in ohms** and corresponds to $R_1$, r is the resistance of the voltmeter and corresponds to $R_2$, E is the voltage of the battery and V is the voltmeter deflection.

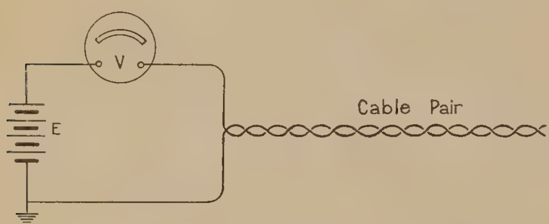



*Figure 50*

**Example:** The voltmeter shown in Figure 47 has a resistance of 100,000 ohms. If it reads 8 volts as shown and 150 volts when connected directly across the battery terminals, what is the insulation resistance of the condenser?

**Solution:** $X = r\left(\frac{E}{V} - 1\right)$

$$= 100{,}000\left(\frac{150}{8} - 1\right)$$

$$= 1{,}775{,}000 \text{ ohms, ans.}$$

**Note:**—Insulation resistance is usually expressed in megohms instead of ohms on account of dealing with high values. One megohm equals one million ohms. Formula 23 may be written

$$X = r\left(\frac{E}{V} - 1\right) \div 1{,}000{,}000,$$

where X is insulation resistance in megohms instead of ohms as in Formula 23.

In the standard testboard circuits dry cell batteries are ordinarily used for insulation testing batteries and these are wired metallic, that is, they have neither the positive nor negative terminal grounded. In some cases, however, it is necessary to measure insulation across a pair of wires such as cable conductors using a permanently grounded testing battery (such as a 120 volt telegraph battery tap). Figure 50 shows such a test but the

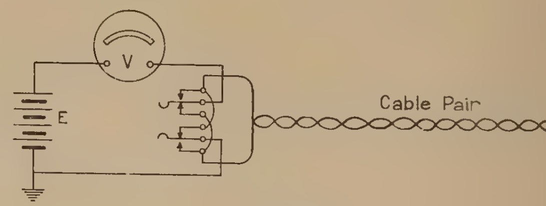



*Figure 51*

metallic or mutual insulation is not distinct from the "wire to ground" insulation on account of one conductor being grounded. It is necessary in this case to take two readings, one with one conductor grounded and the other with the second conductor grounded. Figure 51 shows a reversing key wired in the testing circuit to facilitate this test. While neither of the two readings gives the mutual resistance, it may be calculated if desired from these readings and other readings for single conductor to ground using parallel resistance formulas.

When determining the insulation resistance of open wire or cable pairs, the value is ordinarily expressed as the average resistance per mile rather than a given value for the entire circuit in question. In calculating the resistance per mile value, it is assumed that each mile of wire (or circuit) has a concentrated leak and these are all equal as shown in Figure 52. It is further assumed that the series resistance of the wire is negligible compared with the insulation resistance. Formula 23 when expressed for X equal to the resistance per mile instead of the entire circuit becomes

$$X = r\,l\left(\frac{E}{V} - 1\right) \text{in ohms} \quad \ldots\ (24)$$

$$\text{or } X = r\,l\left(\frac{E}{V} - 1\right) \div 1{,}000{,}000 \text{ in megohms}$$

where l is the length of the circuit in miles.

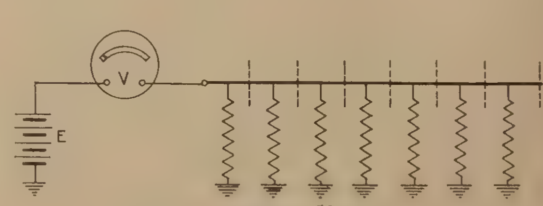



*Figure 52*

**Example:** Assume the wire shown in Figure 52 to be 20 miles long and the voltmeter to have a resistance of 100,000 ohms. What is the insulation of the wire to ground in megohms per mile if battery E.M.F. is 150 and voltmeter reading is 15?

**Solution:**

$$X = r\,1 \left(\frac{E}{V} - 1\right) \div 1{,}000{,}000$$

$$= \frac{(100{,}000 \times 20) \times \left(\frac{150}{15} - 1\right)}{1{,}000{,}000}$$

$= 18$ megohms per mile, ans.

The megger works on the same principle as the series meter method but uses instead of a battery a magneto with a speed governing device, which generates a constant E.M.F. It also uses a meter calibrated to read megohms directly instead of volts. The generator potential is much higher than the battery potentials used for telephone testing, 400 volts being ordinarily used on the more common types. The internal resistance of the meter (and generator) are extremely high and the generated voltage cannot sustain any appreciable current thereby making the instrument safe for practical testing.

CHAPTER VI

# ELECTRICAL MEASUREMENTS FOR DIRECT CURRENT CIRCUITS

(Continued)

## 38. Theory of the Wheatstone Bridge

The Wheatstone bridge has been described as a network of resistances that may be used in connection with a galvanometer to measure unknown resistance values and its theory is the next step in order after the study of the potential drop method of measuring resistance.

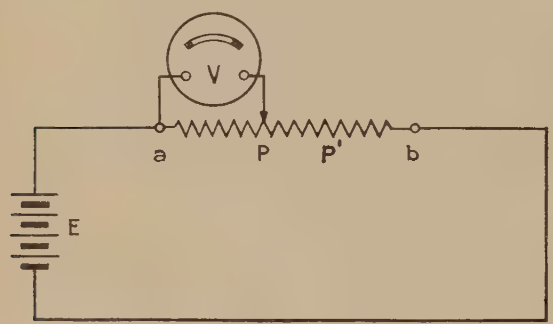



*Figure 53*

In Figure 53 the voltmeter has one terminal permanently connected to **a** and the other terminal may be slid along the resistance **ab.** The voltmeter reading will be zero when both terminals are at **a,** and will gradually increase as the point P is moved toward **b.** We shall find that the potential drop measured between the points **a** and P is always proportional to that part of the resistance between **a** and P, or we may write:

$$\frac{aP}{aP'} = \frac{V}{V'}$$

where V′ is the potential drop measured between **a** and any other point P′.

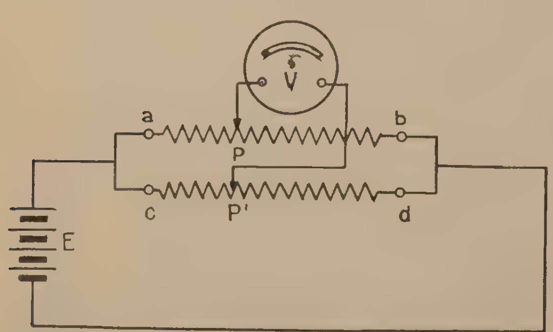



*Figure 54*

If instead of having one resistance, as shown in Figure 53, we have two parallel resistances, as shown in Figure 54, and one terminal of the voltmeter is moved along resistance **ab** while the other terminal is moved along resistance **cd,** we shall find that when that part of the resistance **ab** between the points a and P is proportional to that part of the resistance **cd** between the points c and P′ the difference in potential between the points P and P′ will be zero and there will be no reading of the voltmeter. Mathematically, this may be expressed.

$$\frac{aP}{cP'} = \frac{ab}{cd}$$

Likewise we have a similar expression for the remaining part of the resistance or—

$$\frac{Pb}{P'd} = \frac{ab}{cd}$$

From these two relations we may write:

$$\frac{aP}{cP'} = \frac{Pb}{P'd} \qquad \text{.................... (25)}$$

This merely means that potential drop always distributes itself proportionally along one or more resistances. In Figure 55 let us assume that the resistances represented by the branch A, the branch B, and the branch R, are known, and that the resistance shown as the branch X is unknown. Inasmuch as the meter connected between the points P and P′ is merely being used to determine that these two points have the same potential, a galvanometer can be used instead of the voltmeter and will be preferable in that it is more sensitive. If in Figure 55 there is no deflection in the galvanometer needle we may write the same relation as was given by equation (25)

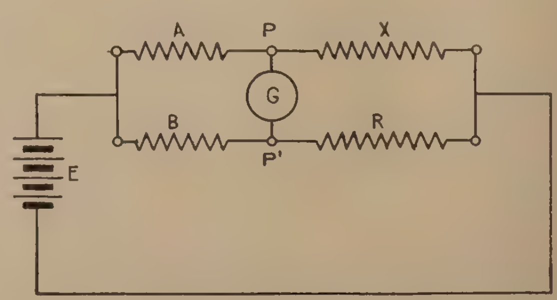



*Figure 55*

$$\frac{A}{B} = \frac{X}{R} \text{ and } \frac{A}{X} = \frac{B}{R}$$

This equation can be expressed:

$$X = \frac{A}{B} R \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

which is the usual equation of the Wheatstone bridge.

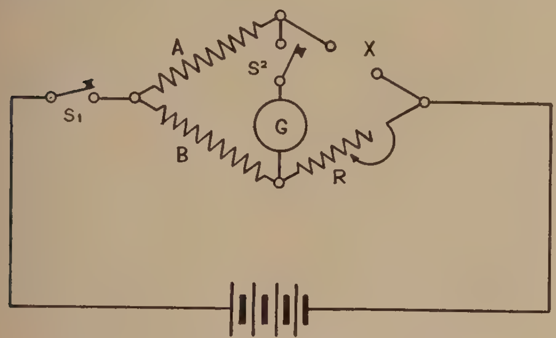



*Fig. 56—Wheatstone Bridge Convention.*

Figure 56 illustrates the conventional method of showing the Wheatstone bridge. It is almost identical to the arrangement shown by Figure 55, but has the resistances connected in a diamond shaped diagram. $S_1$ is a switch for disconnecting the battery when not in use and $S_2$ a similar switch for disconnecting the galvanometer. Binding posts are shown for connecting the unknown resistance to be measured, which is usually designated as X. The resistances A and B are called the **ratio arms** of the bridge and the resistance R is shown as variable so that for any unknown resistance X the value of R may be adjusted to obtain a perfect balance or to bring the galvanometer needle to the stationary or zero point on the scale.

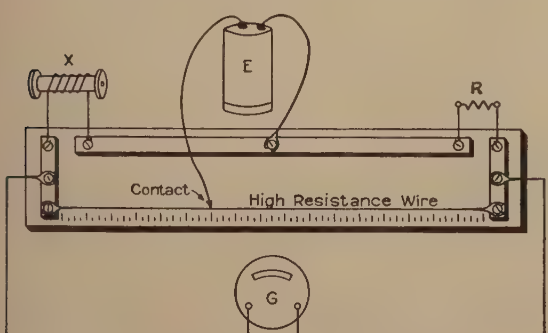



*Fig. 57—Slide Wire Wheatstone Bridge.*

Though Figure 56 shows the resistance branch R as variable and the arms A and B as fixed, a balance could be readily obtained by changing the ratio A/B in Formula 26 instead of varying the value of R. Figure 57 shows a simplified type of Wheatstone bridge that has the value of R fixed and may be balanced in this way. It is known as the slide wire bridge and is shown diagramatically by Figure 58. Its ratio arms are made of a high resistance wire of uniform cross-section mounted over a measuring scale (usually meter stick or yard stick). A sliding contact is connected to the battery. The resistance of the wire between the binding posts on the left and the contact corresponds to

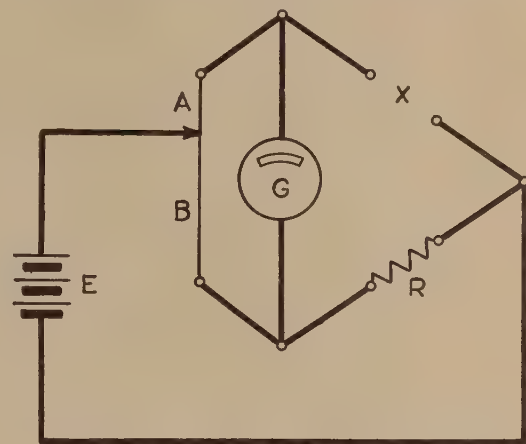


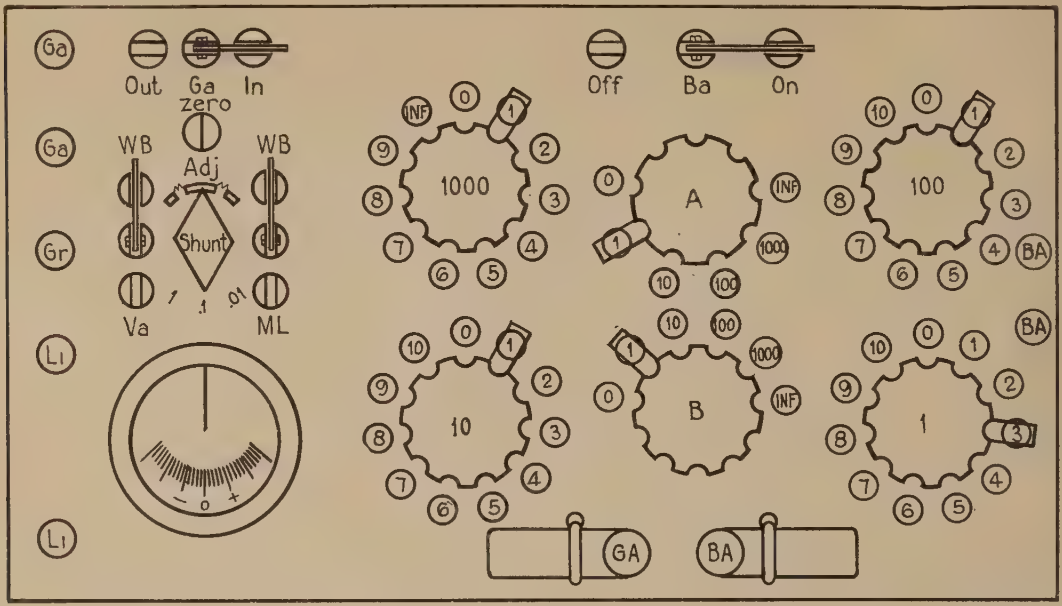

*Fig. 58—Slide Wire Bridge Convention.*

arm A in Figure 56, and the resistance of the wire between the contact and the binding posts on the right corresponds to arm B in Figure 56. R has a constant value, and may be any convenient resistance of known value. The connections are all made to binding posts mounted on heavy copper straps which have negligible resistance values.

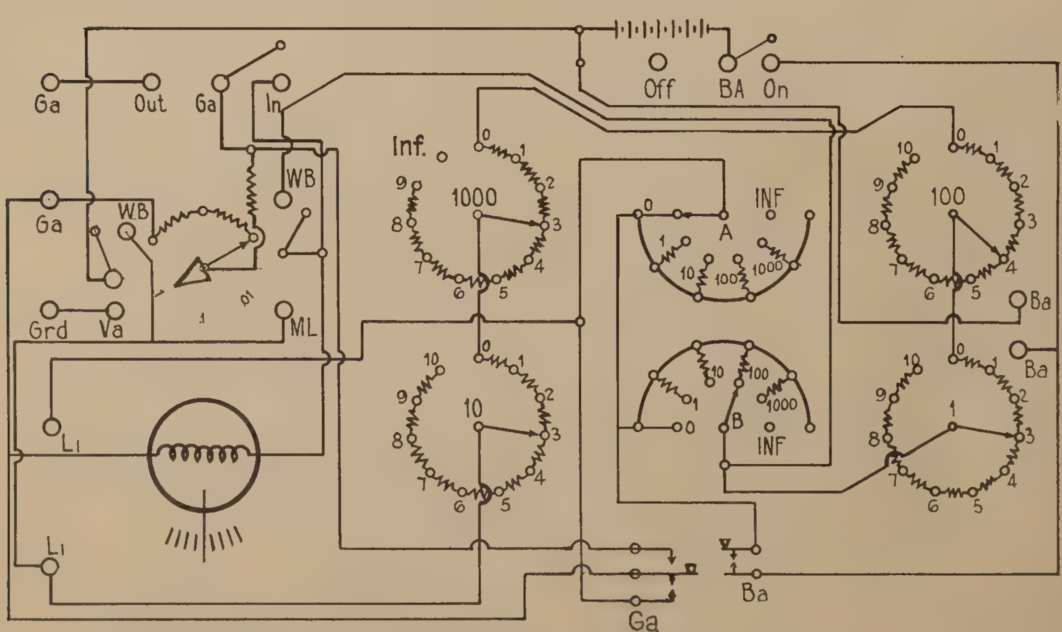
In all forms of the Wheatstone bridge it is permissible to reverse the connections for the battery and the galvanometer in so far as these connections concern the theory of operation. Thus, in Figure 57 the galvanometer and dry cell could be interchanged without in any way affecting the operation of the bridge.


*Figure 59*

There are many commercial types of Wheatstone bridge testing instruments. There are three in particular that are used extensively in telephone and telegraph work. One is a small portable type, known as a Peerless testing set. It is standard for portable use and for mounting on the key shelf of the #12 local test desk. The others are especially designed bridges for use in connection with the #4 and #5 toll testboards and are known as the "#12001 Bridge" and the "Wheatstone Bridge per KS-3011", respectively. The dial and circuit arrangements of these bridges are shown by Figures




Dial Arrangement.




Wiring Diagram.

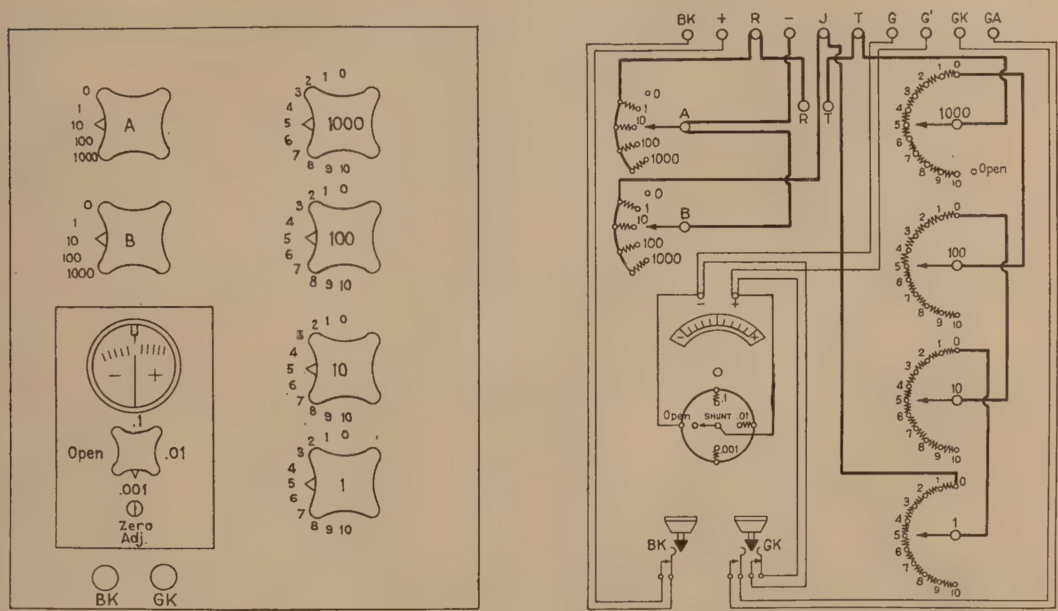
*Fig. 60—Peerless Testing Set.*

60, 61 and 62 and the theory is shown by Figure 59. The Peerless testing set has both the battery and galvanometer mounted inside the case. It contains resistance coils of manganin wire non-inductively wound on spools and accurate to within .1 to .01 of one per cent. The set is arranged for making simple resistance measurements, Varley loop tests, and Murray loop tests. The arms A and B are each adjusted by dials, giving values of 1 ohm, 10 ohms, 100 ohms, and 1,000 ohms for each arm. Four other dials permit any value for the variable resistance R from 1 ohm to 11,000 ohms. The galvanometer is equipped with resistance shunts of varying values which protect it while a balance is being secured.

accurate. It employs a reflection type galvanometer having a lamp and scale instead of a needle which permits the detection of smaller current values than is possible with the preceding types of bridges. The ratio arms are controlled by a single dial which gives the ratio A/B directly for nine values as follows:

$$1000,\ 100,\ 10,\ 1,\ \frac{1}{4},\ \frac{1}{9},\ \frac{1}{10},\ \frac{1}{100},\ \text{and}\ \frac{1}{1000}.$$

The rheostat arm has a total resistance of 9999 ohms and is adjustable by means of four inverted dials in steps of one ohm. The resistances in the rheostat




Dial Arrangement

Wiring Diagram.

*Fig. 61—No. 12001 Wheatstone Bridge designed for Use in Connection with No. 4 Testboard.*

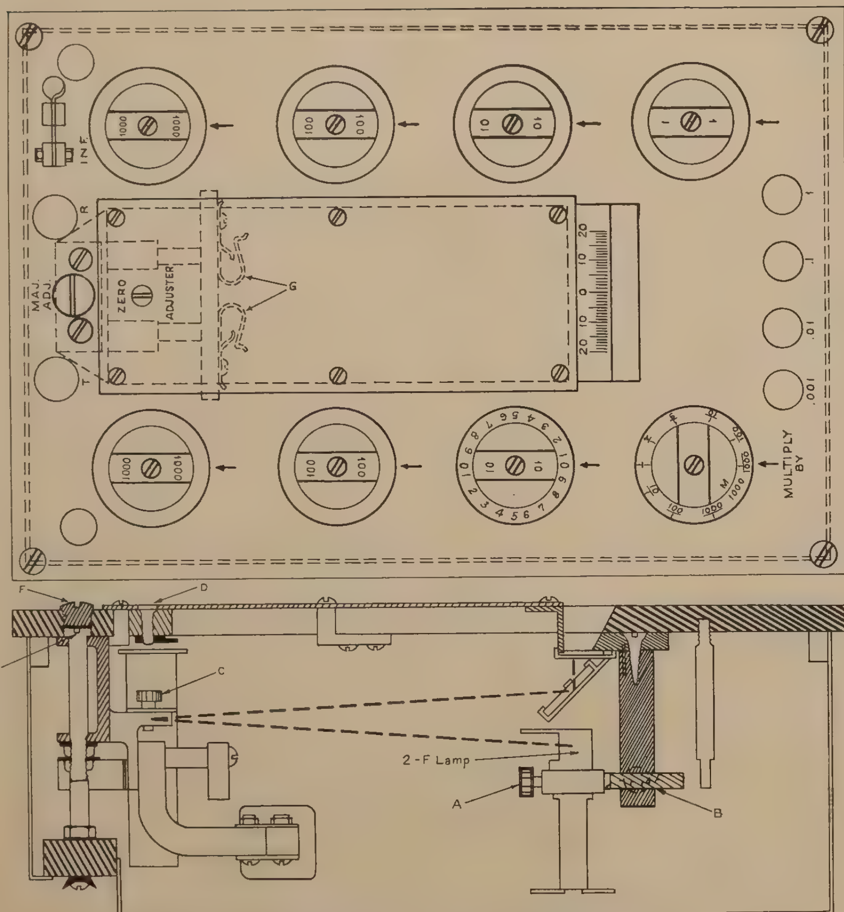
The #12001 bridge is especially designed for the #4 testboard testing circuit. The galvanometer is mounted in a separate case which in turn mounts inside the bridge case in such manner that it may be conveniently removed. All connections are brought out to binding posts so that various testing combinations can be secured with the particular key arrangement of the #4 testboard testing circuit. The galvanometer is equipped with resistance shunts and has a coil resistance of 288 ohms. Dials are used for the A and B arms and for the variable balancing arm in the same manner as for the Peerless testing set, but no sliding contacts are exposed.

The Wheatstone bridge per KS-3011 is designed for use in the #5 toll testboard and is of a type similar to the #12001 bridge but is somewhat more

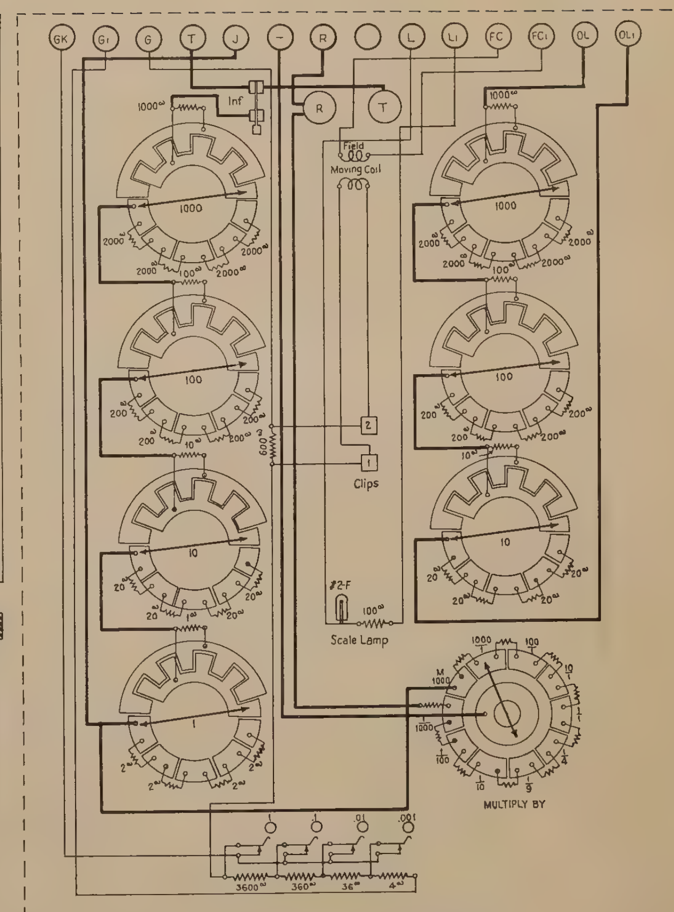
arm are accurate to 1/10 per cent and in the ratio arms to 1/20 per cent. Three additional dials are provided for use in connection with open-location tests.

### 39. Simple Loop Tests or Plain Resistance Measurements

In the telephone and telegraph plant the Wheatstone bridge is used extensively in locating faults in both open wire circuits and cable pairs. The simplest test of this kind is the location of a cross between two wires. Figure 63 shows the Wheatstone bridge connected to the office end of a cable pair which has its conductors crossed together some distance from the office. If the cross itself has zero resistance (i.e., if the wires are "dead




Dial And Galvanometer Arrangement




Wiring Diagram

*Fig. 62—Wheatstone Bridge Per KS-3011 For Use With No. 4 And No. 5 Toll Testboard.*

crossed") the location is a simple one. The unknown resistance as measured is merely the loop resistance for the length of cable conductors from the office to the point of the defect and this length may be easily determined from the resistance measurement and the values given in Table IV.

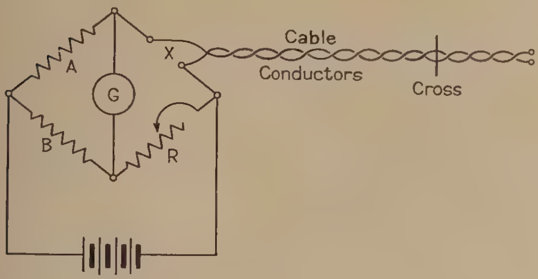



*Figure 63*

**Example:** In Figure 63 the cable conductors are #19 B. & S. gauge, and the cross between conductors is assumed to have zero resistance. If the value of X, as measured by the Wheatstone bridge, is 55 ohms, how far is the cross from the telephone office?

**Solution:** Let d = distance in miles

Loop resistance of cable per mile from Table IV = 85.01 ohms

X = 55 ohms

d = 55 ÷ 85.01 = .657 miles, Ans.

If the cross shown in Figure 63 should itself have a resistance value, which is quite often the case, the value of X as measured by the Wheatstone bridge would be equal to the loop resistance of the cable conductors from the office to the defect plus the resistance of the cross itself, and in this case the defect on account of having a definite value might be located at any intermediate point between the office and .657 miles from the office. It is, therefore, necessary in using the loop method to make two measurements to accurately determine the location of any cross when it is not definitely known that it has zero resistance. The simplest way to determine if it has zero resistance is to make one measurement with the distant end of the cable pair open and another with the distant end of the cable pair short circuited. **If these two measurements are the same, which means that opening or closing the distant end of the cable pair does not in any way affect the measurement, the cross is known to have zero resistance** (dead crossed). If the measurement with the distant end of the cable pair crossed is lower in value than the measurement with the distant end of the cable pair open, the cross itself has some definite resistance value, and the location, instead of being .657 miles away, is some point between .657 miles away and the office. One way to determine the exact location in this case is to make loop measurements from each end of the cable pair, and to calculate an imaginary location from each measurement on the assumption of a zero cross. The location when calculated from the measurement made at the office end will be too far away, and when calculated from the measurement made at the distant end will be too near the office. The actual location is the mean or point half way between the two. Of course, in practice it is often times not convenient to transfer the Wheatstone bridge to the distant end of the circuit in order to make measurements from that end. A substitute for this method which amounts to the same thing, is to connect the distant end of the defective pair to a good cable pair as shown in Figure 64. This permits testing in both directions from the same office. If the exact length of the good pair is not known, it can always be determined by making a measurement with the distant end crossed.

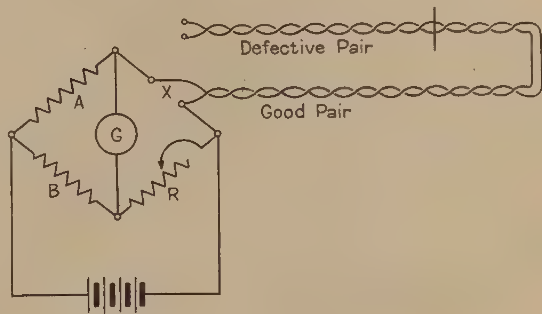



*Figure 64*

**Note:**—It will be learned in the next Article that the quickest and most accurate method of locating a cross in practice is by the metallic Varley. But the theory underlying the foregoing should be thoroughly mastered before taking up the more special tests.

**Example:** In Figure 64 the good cable pair when short-circuited at the distant end has a loop resistance of 63 ohms. When connected to the defective pair as shown, the measurement from the office to the cross over the good pair and the distant end of the defective pair is 108 ohms. The measurement from the office to the cross on the defective pair is 37 ohms. What is the distance in miles from the office to the defect, and what is the resistance of the cross if cable pairs are 19 B. & S. gauge?

**Solution:** Assume first that cross has zero resistance. Imaginary distance from office according to measurement on defective pair is as follows:

$$d_1 = \frac{37}{85.01} = .435 \text{ miles}$$

Length of good pair is as follows:

$$1 = \frac{63}{85.01} = .74 \text{ miles}$$

Imaginary distance from distant end is as follows:

$$1\text{—}d_2 = \frac{108}{85.01} - .74 = .53 \text{ miles}$$

Then actual cross is at point half way between .435 miles from near office and .53 miles from distant office or .74 — .53 = .21 miles from near office. Actual location is

therefore $\frac{.435 + .21}{2} = .323$ miles, ans. Resistance of cross caused an error in the single measurement location of .435 — .323 = .112 miles of cable pair. This expressed as resistance is .112 x 85.01 = 9.5 ohms, ans.

Another practicable application of the simple loop resistance measurement is to determine any inequality in the resistance of individual conductors, or as is commonly expressed, to locate resistance unbalances due to such causes as defective splices in cable pairs or defective sleeve joints in open wire. This test, requiring at least three conductors, is ordinarily made by having the conductors crossed at the distant end and making measurements on various combinations:

**Example**: It is desired to determine the amount of resistance unbalance for conductors of a phantom group between points A and B. Wheatstone bridge is located at A. The wires are designated 1, 2, 3 and 4 and the testboard man at B has crossed all four wires together.

**Procedure**: Measure loop resistance with bridge connected to wires 1 and 2. Let us assume reading of 90 ohms.

Measure loop resistance with bridge connected to wires 2 and 3. Let us assume reading of 90 ohms.

Measure loop resistance with bridge connected to wires 1 and 3. Let us assume reading of 88 ohms.

Measure loop resistance with bridge connected to wires 1 and 4. Let us assume reading of 88 ohms.

**Solution**:
$W_1 + W_2 = 90$ .......... (a)
$W_2 + W_3 = 90$ .......... (b)
$W_1 + W_3 = 88$ .......... (c)

Subtracting equation (b) from equation (a) we have

$W_1 - W_3 = 0$ .................. (d)

Adding (c) and (d) we have

$$2W_1 = 88, \text{ or } W_1 = 44 \text{ ohms}$$

Substituting in (a) we have

$$44 + W_2 = 90 \text{ ohms}$$
$$\text{or } W_2 = 46 \text{ ohms}$$

Substituting in (c) we have

$$44 + W_3 = 88 \text{ ohms}$$
$$\text{or } W_3 = 44 \text{ ohms}$$

And since $W_1 + W_4 = 88$ we likewise have

$$44 + W_4 = 88$$
$$\text{or } W_4 = 44 \text{ ohms}$$

Thus we learn $W_2$ has resistance unbalance of 2 ohms, Ans.

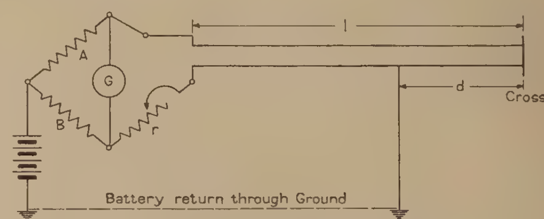
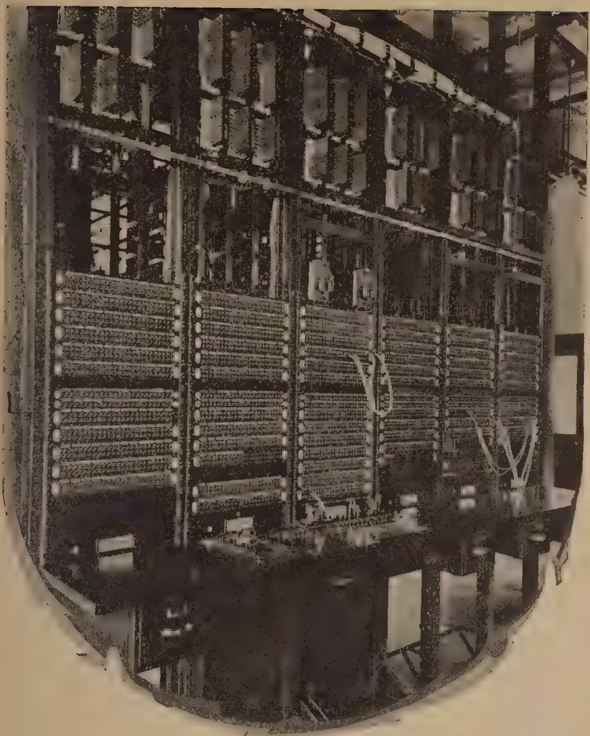


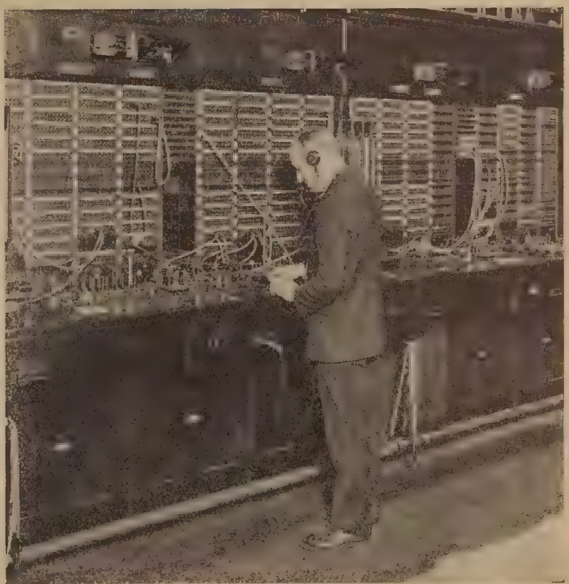

*Figure 65—Grounded Varley Test.*

## 40. Varley Loop Tests

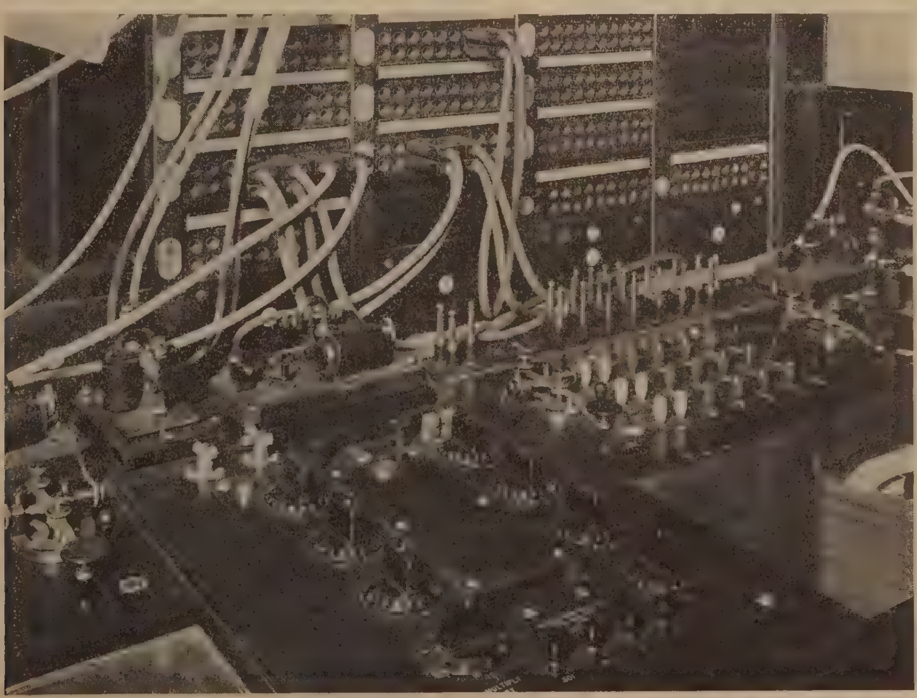
A Wheatstone bridge may be used to locate a defect due to a grounded wire or cable conductor as well as a defect due to a cross between conductors. There are two recognized methods of making tests of this kind. One is known as the Varley loop test and is the more generally used; the other is known as the Murray loop test. Figure 65 shows the theory of the Varley loop test. In comparing this figure with Figure 56, we can recognize a Wheatstone bridge circuit with the connections made in a little different way. The Wheatstone bridge arm which is shown in Figure 56 as the variable resistance R is shown in Figure 65 as the variable resistance r in series with the resistance of the defective wire from the office to the point where it is grounded. The resistance in Figure 65 corresponding to X in Figure 56 is the series resistance of the good wire of the circuit from the office to the distant end plus the resistance of the defective wire from the distant end to the defect. The battery connection is made through the ground to the fault itself. When a balance is obtained in this circuit, the value of r instead of corresponding to the value of R in formula 26 is equal to the loop resistance of the circuit from the defect to the distant end, providing the arms A and B are of equal value. This can be seen by inspecting the circuit, for it is evident that the adjustment of the r arm of the bridge is merely used to insert resistance in series with the defective wire and its value when the bridge is balanced corresponds to the loop from the defect to the distant end.

## TOLL TESTBOARDS





*Above*—An installation of No. 5 type toll testboards.
*Right*—General view of No. 4 type toll testboard.
*Below*—Close-up of No. 4 testboard position showing testing keys and cords and Wheatstone Bridge per KS-3011.



**Example:** In Figure 65 the bridge is connected to a 30 mile non-loaded circuit of 104 copper wire. Each of the arms A and B is set on 1000 ohms. If the reading for the value r is 22 how far is the ground from the office making the test?

**Solution:** Table IV gives 10 ohms per mile for the loop resistance of 104 copper wire. Measurement of 22 ohms represents resistance of loop from defect to distant office which distance is $\frac{22}{10} = 2.2$ miles. If circuit is 30 miles long defect is located $30 - 2.2$ or 27.8 miles from office making the test, Ans.

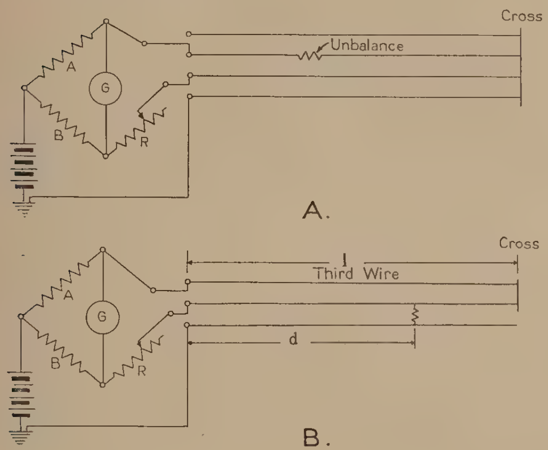



*Fig. 66—Metallic Varley Tests.*

A modification of the Varley test may be used for accurately measuring resistance unbalances and is in some respects preferable to the method of combination loop measurements described in the foregoing article. It is called the metallic Varley, and is shown by Figure 66-A. In making this test all wires are short-circuited at the distant end in the same manner as when making a series of loop tests for the various combinations of wires. At the testing office one wire of the combination is grounded, and this is used for the battery return instead of the circuit formed by grounding at the distant office. Two of the remaining wires are then connected to the Wheatstone bridge and R is adjusted to give a balance. If a balance cannot at first be secured this indicates that the higher resistance wire is in series with R and the connections to the bridge terminals are reversed. If the arms A and B are equal, the value of R then obtained represents the difference between the resistance of the two wires, and no calculations are required. When all combinations of wires are tested by the metallic Varley excepting the grounded wire, the grounded wire may be interchanged with any one of the others and included in the tests.

A modification of this test requiring only three wires is commonly used in testboard work for locating crosses, particularly those having high resistance. As noted in the preceding Article, the location of a cross having resistance by the use of loop resistance measurements involves certain difficulties. By using a good third wire of the same gauge as that of the pair in trouble and connecting the bridge for a metallic Varley measurement as shown in Figure 66-B, however, the resistance of the cross is removed from the "balanced" circuit of the bridge and placed in the battery circuit, where it has no effect on the measurement providing its resistance is not so high as to prevent sufficient current being supplied to the bridge to permit of its being accurately balanced. As may be seen from the diagram of connections, where the bridge is balanced with equal values in the ratio arms A and B, the resistance of the good third wire plus the resistance of one wire of the crossed pair from the distant end to the fault is equal to the resistance of one wire from the fault to the measuring end plus the resistance, R, in the rheostat arm of the bridge, or we may write

$$l + (l - d) = d + R$$

from which $$d = \frac{2l - R}{2}$$

In locating a cross by this method in practice it is only necessary to make a Varley measurement as described above and a loop resistance measurement on the pair consisting of the good third wire and one wire of the crossed pair shorted together at the distant end. Then the loop resistance of the crossed pair from the measuring end to the fault may be obtained directly by subtracting the Varley reading from the loop resistance reading.

The Varley test may also be used for locating a cross between one wire of a circuit and some other wire such as one wire of an iron circuit where the series resistance of the second wire per loop mile is not accurately known or when the loop method may be inaccurate due to the resistance of the cross, which cannot be determined by the two measurement method. The procedure here is to ground the iron wire or wire of the second circuit, cross the first circuit at the distant end, connect the bridge to it and locate the ground by the Varley method which is equivalent to locating the cross.

## 41. Murray Loop Tests

The theory of the Murray loop test is similar to that of the Varley, but instead of setting the arms A and B to have equal values and using the adjustable dials to compensate for the difference in wire resistances between the good wire connection and the defective wire connection, the arm B is eliminated altogether and the variable resistance arm is connected in its stead as shown in Figure 67. In this arrangement the ratio of the reading R to the setting of the arm A is equal to the ratio of the re-

sistance of the defective wire from the measuring office to the ground to the resistance of this same wire from the ground to the distant office plus the resistance of the good wire, or expressed mathematically

$$\frac{R}{A} = \frac{\text{resistance of } 1 - d}{\text{resistance of } 1 + d}$$

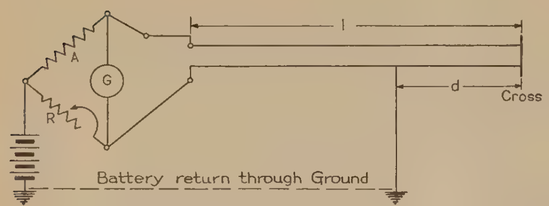



*Figure 67*

providing the defective and good wires used in making the test have the same series resistance per mile, as would ordinarily be the case where for any given circuit being tested the defective wire's mate is used.

**Example:** In Figure 67, arm A is set for 1000 ohms, and the bridge is balanced by varying the arm R. If the value of R is 634 ohms and the length of the circuit under test is 65 miles, what is the distance from the testing office to the fault?

**Solution:** The simple bridge relation gives

$$\frac{R}{A} = \frac{\text{resistance of } 1 - d}{\text{resistance of } 1 + d}$$

or, $$\frac{634}{1000} = \frac{(65 - d) \text{ x res. per mile}}{(65 + d) \text{ x res. per mile}}$$

or if resistance per mile of each wire is the same this factor will cancel and

$$\frac{634}{1000} = \frac{65 - d}{65 + d},$$ which gives by cross multiplying

$$634\ (65 + d) = 1000\ (65 - d),$$

or, $1634\ d = 23790$

from which $d = 14.56$ miles

or, $1 - d = 50.4$ miles, Ans.

There are a number of other standard tests made with the Wheatstone bridge and with these as well as with the tests that have been described the procedure in practice is somewhat more involved than the simple theory might indicate. There are in nearly all practical tests various complicating factors such as temperature variations, effect of loading coils, short lengths of cable, irregular facilities, etc. which must all be considered if accurate locations are to be made. The details of how these various factors are taken care of in practice present a complete study in themselves, however, and their consideration is necessarily beyond the scope of this Course.

### 42. Precautions to be taken in the Use of Measuring Instruments

The intelligent use of the electrical measuring instruments described in this chapter and in Chapter V depends upon skill and care as well as upon an understanding of the theory of each test made. There are numerous precautions to be taken, some of which are to be learned only through experience, but a few cardinal ones are listed here and may be studied accordingly. In the use of all testing instruments there is one important motive,—the most accurate results possible should be secured without damaging the measuring instruments.

a. **Precautions should be taken against dropping or jarring** electrical measuring instruments, particularly galvanometers, voltmeters, ammeters, and wattmeters. Instruments of this latter class have revolving coils, either suspended in a delicate manner or equipped with jewelled bearings. Jarring may permanently damage the instruments or impair their accuracy.

b. Electrical measuring instruments should be **kept free from dampness.**

c. Instruments should **never** be **connected to circuits where the values** to be measured **are likely to be greater than the highest scale reading,** and the low resistance coils of a Wheatstone bridge should not have E.M.F.'s impressed across them sufficiently high to cause currents greater than the carrying capacity of these coils. In general, for ordinary testing, the A and B arms should not be set upon low values if the voltage of the testing battery is comparatively high.

d. **Milliammeters and millivoltmeters are designed for measuring millivolts and milliamperes, not volts and amperes.**

e. **Ammeters must always be inserted in series** and never across any branch or any part of an electrical circuit.

f. In any Wheatstone bridge test, **the galvanometer** and the **battery key should not be closed excepting when the tester is actually endeavoring to obtain a bridge balance.** If the galvanometer is equipped with a shunt, **the lowest resistance shunt should be bridged across the galvanometer when beginning to obtain a balance.** When an approximate balance is obtained in this way, the next lowest value shunt should be bridged, and thus by degrees the galvanometer coil may be connected into the circuit.

g. In making Wheatstone bridge measurements, **precautions should be taken against extraneous sources of E.M.F. such as ringing current, cords with battery, telegraph legs, etc.** being connected to the circuit at the distant end or at some intermediate point while the Wheatstone bridge test is being made.

h. For accuracy when reading scales of electrical instruments **the eye should be directly over the needle,** that is, the line of vision should be perpendicular to the scale. Some instruments are equipped with small mirrors beneath the needle in order to avoid reading the scale at an angle. When the image of the needle in the mirror is directly beneath the needle, the eye is perpendicular to the scale. An error caused by **the eye not being perpendicular to the scale** is called error due to **parallax.**

i. Some instruments are designed for reading when mounted vertically; others for reading when mounted horizontally. In general, all portable instruments are designed for reading horizontally. Permanently mounted instruments such as meters for power boards, etc. are usually designed for reading when vertical.

j. When an indicating instrument is not connected, the **needle should stand on zero of the scale.** Most instruments are equipped with some device such as a screw head adjustment for correcting the zero position of the needle.

k. Delicate instruments are usually equipped with some device for **clamping the needle when not in use.** This often prevents damage from jarring. Instruments not equipped with a clamping device may have their coils "dampened" by short-circuiting their terminals. Care must be taken that the short-circuit is removed before using the instrument.

l. Errors are often encountered in Wheatstone bridge measurements on long open wire and cable circuits due to foreign potentials caused by induction, ground potentials, etc. To correct for these, it is often necessary to reverse the polarity of the testing battery and make a second measurement. The average of the two measurements may be recorded as the correct one.

m. In making Wheatstone bridge measurements, precautions should be taken that the circuit under test is absolutely cleared of all bridged or other apparatus not permanently associated with the circuit and essential for giving simple continuity.

n. **Beware of loose connections.** Make sure that all connections to binding posts or elsewhere have zero resistance. Do not use high resistance wires for leads.

o. **Make a mental estimate of the value you expect to read** from your knowledge of the conditions. This will often prevent mistakes due to errors that are obvious and will usually prevent the improper use of the instruments.

**Note:**—It should be appreciated that in this Chapter no attempt has been made to describe all of the D.C. tests commonly used in locating troubles in the telephone plant nor to point out the various special methods and short-cuts used in practical testboard work. It has been the intent, rather, to treat a few of the outstanding testing methods in a theoretical way, thereby establishing the general principles upon which all testing work is based.

# CHAPTER VII

## THE DIRECT CURRENT DYNAMO—ELECTRIC MACHINE

### 43. Induced Electromotive Force

Chapters III and IV described how lines of force exist around any wire in which current is flowing. Not only does an electrical current establish such a field, but similarly a magnetic field can be made to create an electromotive force. Voltage may be induced in any conductor by moving it through a magnetic field in such a manner that it "cuts" the magnetic lines of force. If the wire indicated in cross-section by the circle in Figure 68 is moved

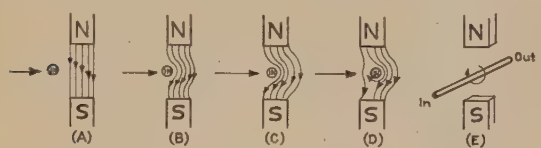



*Fig. 68—Effect of Wire Moving Through Magnetic Field.*

horizontally to the right through the lines of force having a direction vertically downward, it will displace or "stretch" the lines of force, which possess a certain elasticity, and will finally break them and cause them to wrap themselves around the conductor. Referring to Figure 38 in Chapter IV and applying this figure conversely to our new conditions, we find that a magnetic field which loops around a conductor in a clockwise direction gives rise to a current flowing **into** the conductor, as seen in cross-section. This is illustrated in Figure 68 (D and E).

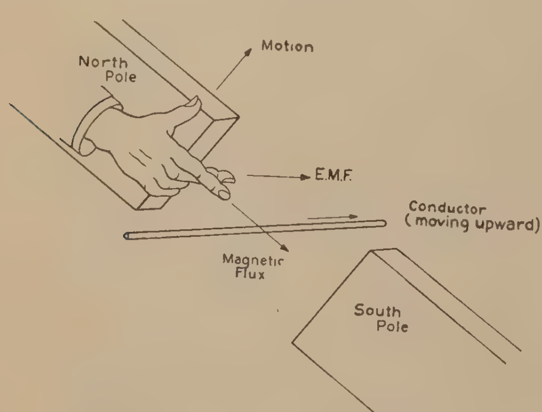



*Figure 69—Right Hand Rule.*

This rule, stated in another way, is called the **"right-hand rule"** for remembering the induced E. M. F. relation, and is illustrated in Figure 69. The forefinger of the right hand represents the direction of the lines of force (flux—north to south); the thumb, when pointed perpendicular to the forefinger, represents the direction in which the conductor moves; and the second finger, when perpendicular to both the forefinger and the thumb, gives the direction of the induced E.M.F. or the direction of current flow. If a galvanometer is connected to the conductor, as in Figure 70, it will be found that the effect is more noticeable when the conductor is moved swiftly. From these and other similar experiments we learn that the law for induced E.M.F. may be stated as follows:

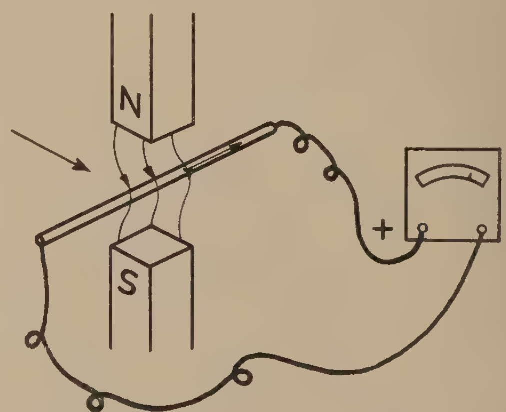



*Fig. 70—Induced E. M. F. Causing Galvanometer to Deflect.*

**When any conductor is made to cut lines of force, there will be an E.M.F. induced in it, and the direction of the E.M.F. the direction of the flux, and the direction of the motion of the conductor have a perpendicular relation as shown by the right-hand rule. The amount of induced E.M.F. depends upon the rate of cutting lines of force or the number of lines cut per second. From the established system of electrical and magnetic units which have been scientifically chosen, an E.M.F. of one volt is induced when a conductor cuts 100,000,000 lines of force per second.**

### 44. E.M.F. Induced in a Revolving Loop

If, instead of a single conductor cutting lines of force, we have a loop of wire revolving in the magnetic field between the poles of a magnet, as shown in Figure 71, and the conductor nearest the south pole moves to the left, while the conductor nearest the north pole moves to the right, the E.M.F. induced has a different direction in the two conductors. But, on account of the loop being complete, these E.M.F.'s will aid in causing a continuous current flow in the direction a-b-c-d, as shown by Figure 72-A. The values of these E.M.F.'s will depend,

however, upon the position of the loop. If the plane of the loop becomes perpendicular to the magnetic field as in Figure 72-B, each conductor will be moving parallel to the direction of the lines of force, the loop will be in a neutral position, and the generated

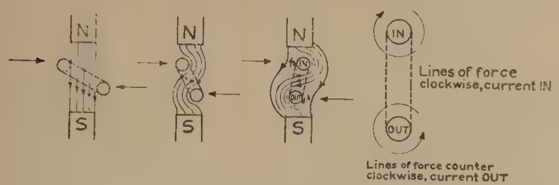



*Fig. 71—Two Wires Cutting Field in Opposite Directions.*

E.M.F. will have decreased to zero. If the loop is then turned through an angle of 90° in the same direction (Figure 72-C) it will again be cutting lines of force at the maximum rate, but the E.M.F. will be reversed with respect to the loop itself and the current will flow in the direction d-c-b-a, or opposite to the flow in Figure 72-A.

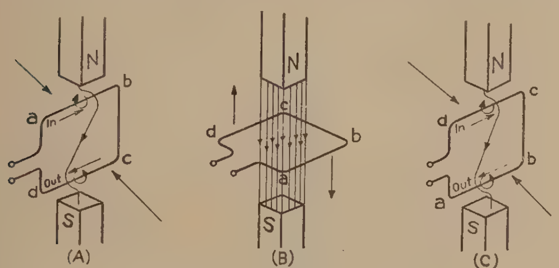



*Fig. 72—Loop of Wire Rotating in Magnetic Field.*

With the loop revolving at constant speed, the E.M.F. induced in it and the resultant current are proportional to the number of lines of force cut, which in turn are proportional to the **horizontal motion** of each conductor of the loop. The maximum E.M.F. is induced when the plane of the loop is parallel with the lines of force and the minimum (zero) when it is perpendicular to the lines of force. At every intermediate point the value of the E.M.F. may be determined by the horizontal motion of the loop per angular degree through which it turns.

Figure 73 shows a mechanism which will illustrate the way in which this current varies. Wheel **d** is rotating at a constant speed, causing attached pin **a** to slide in slot **o**, moving bar **b** (with pencil **e** attached) vertically between guides **gg**. When the horizontal component of the motion of the pin **a** is a maximum, that is, when the motion is in an entirely horizontal direction, the pencil **e** will be at either its highest or lowest position, depending upon whether the motion of **a** is from left to right or right to left. When the horizontal motion of **a** is zero, **e** will be midway between its extreme high and low points. If **f** represents a strip of paper which is being moved horizontally to the right at a constant speed while wheel **d** is also rotated at a constant speed, the pencil **e** will draw a curve as shown. This curve will indicate a positive maximum (or highest point) when the horizontal motion of **a** to the right is a maximum; and will indicate center or zero points when the horizontal motion of **a** is zero. If the pin in this mechanism represents one conductor of a loop of wire revolving in a vertical magnetic field, the position of pencil **e** with respect to the midpoint

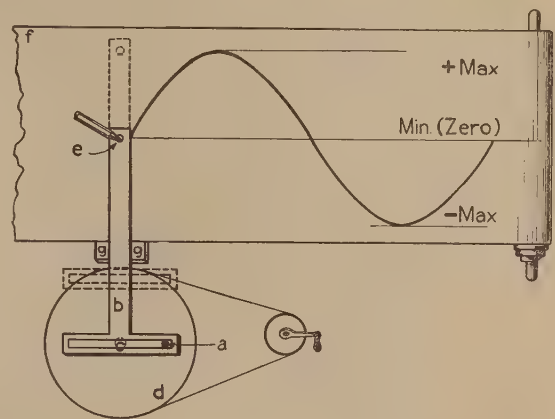



*Fig. 73—Sine Wave Mechanism.*

of its travel represents the E.M.F. induced in the conductor. This analogy is apparent since the induced E.M.F. in each loop is proportional to the horizontal motion of the loop and the curve not only represents maximum and zero points but shows all intermediate values of the induced E.M.F. as well. This curve is called a **sine wave** and is the standard **fundamental** wave form in alternating current circuits of all kinds.

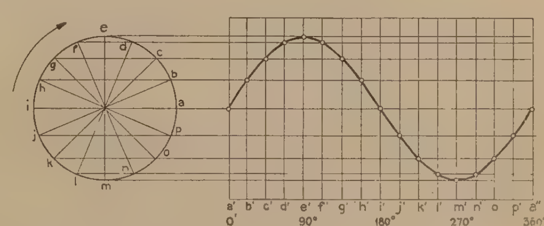



*Fig. 74—Graphical Construction of Sine Wave.*

A sine wave may be actually plotted by the method shown in Figure 74, where the horizontal lines are continuations of points a, b, c, etc. and the vertical lines a′, b′, c′, etc. are equally spaced and in**dicate angular degrees of rotation.** The intersections of lines a and a′, b and b′, etc. indicate points on the sine curve. The line d is also a continuation of point f, as c continues g, etc. permitting the location of f, f′, g,g′, h,h′, etc.

## 45. Principle of the Direct Current Generator

The revolving loop or **armature** shown in Figure 72 may be connected to slip rings, as shown in Figure 75-A, in which case the resulting E.M.F. between the two terminals or **brushes** will reverse in direction as the loop revolves, giving rise to an **alternating** E.M.F., one **cycle** of which is plotted in the figure. If it is desired to produce a unidirectional E.M.F., it is necessary to devise some means for reversing the connections to the loop at the same time that the current in the loop reverses. This is done by means of the **commutator** shown in Figure 75-B. This commutator effects the reversing of the connections to the armature leads, just as the E.M.F. or current is reversed, changing the negative half cycle shown in the graph, to a positive pulsation. The resultant E.M.F., then, consisting of two positive pulsations per revolution of the loop.

Generators may be constructed with more than one loop, as in Figure 76, in which two loops and four commutator segments are shown. The resultant E.M.F. is represented by the full lines in the graph in the figure.

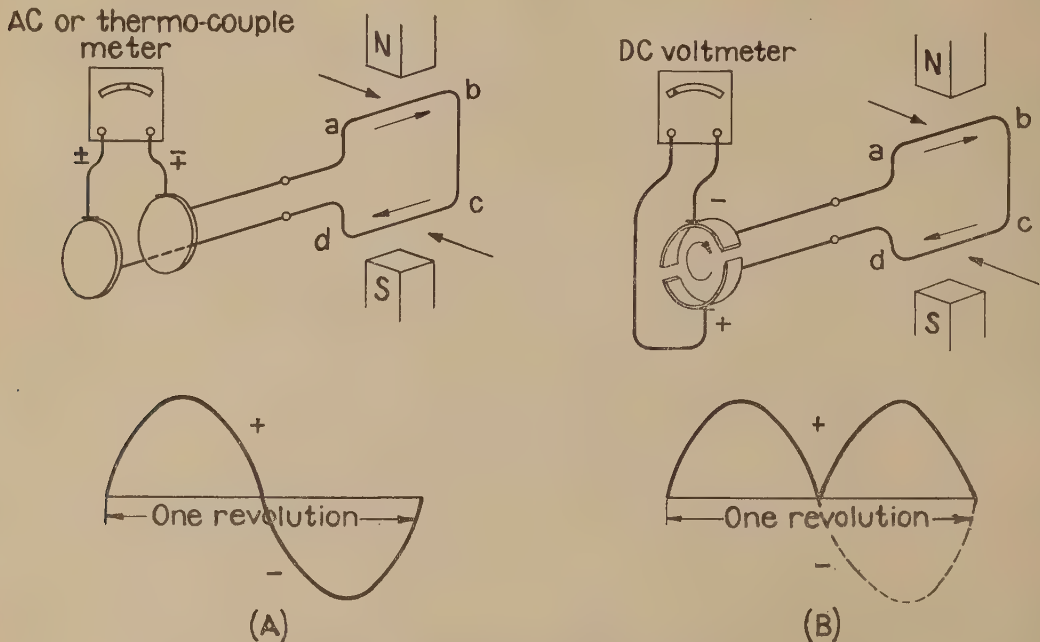



*Fig. 75—Method of Connecting to Loop.*

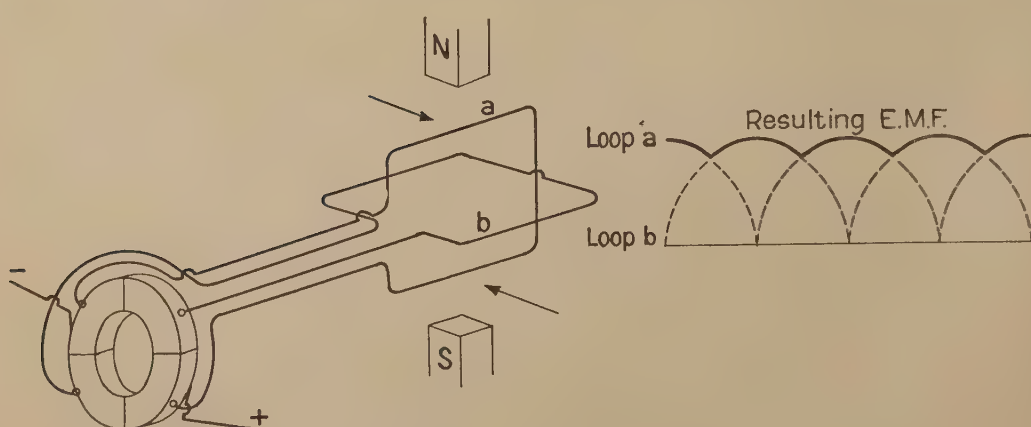



*Fig. 76—Two Loop (4 Segment Commutator) Generator.*

Comparing Figure 75-B with Figure 76, it may be seen that an increase in the number of loops causes a similar fluctuation in the armature E.M.F. so that an armature wound with many turns produces a practically continuous non-pulsating E.M.F., causing a direct current.

A standard generator armature consists of a large number of loops or turns which may be wound in several ways, depending upon the number of poles and the speed and voltage desired. The actual winding, however, consists of one continuous conductor, from which taps are brought out and con-

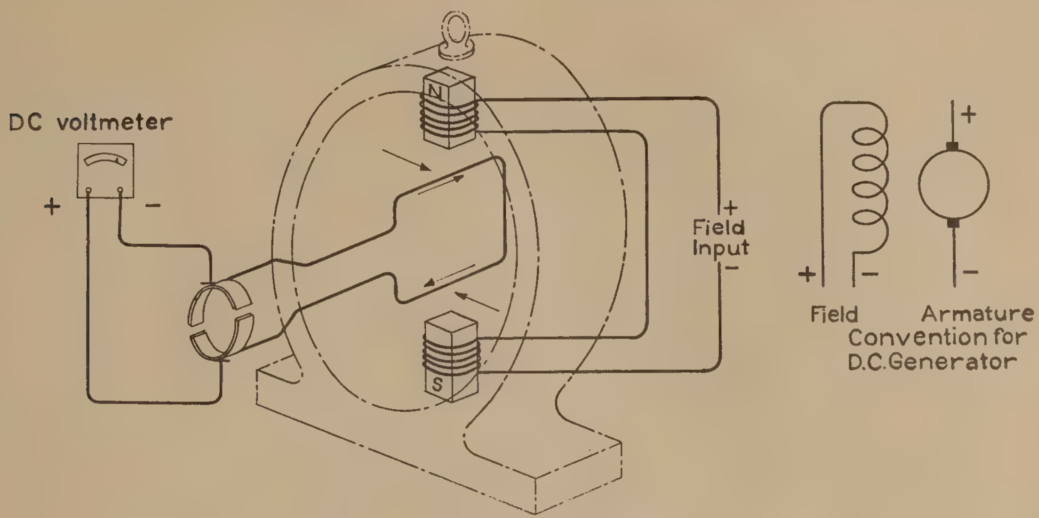



*Fig. 77—D. C. Generator Circuit.*

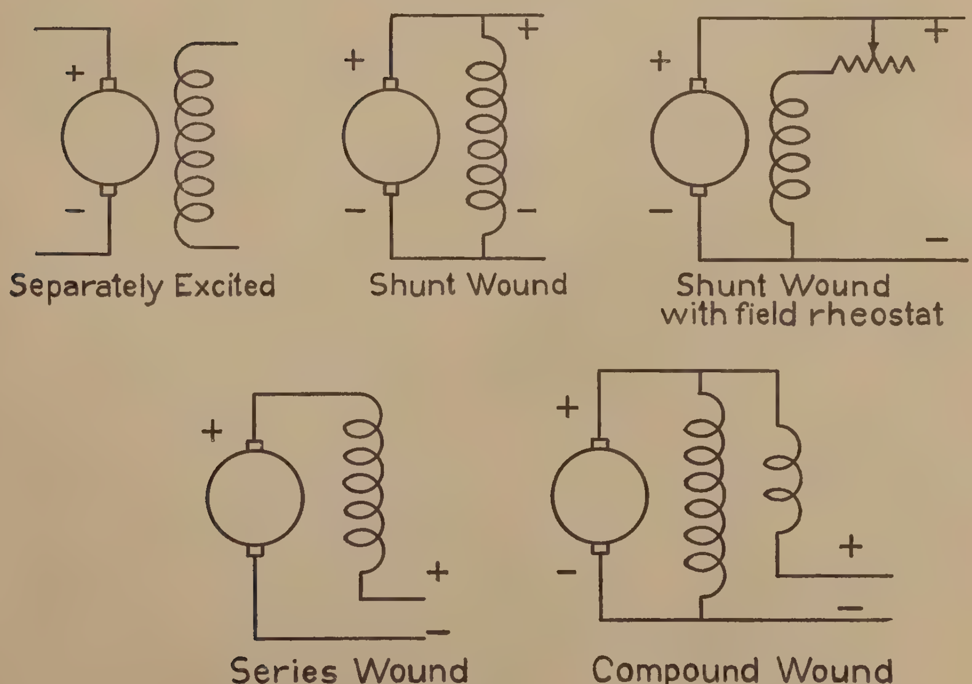



*Fig. 78—Schematic of D. C. Generators.*

nected to commutator segments, instead of a large number of separate loops.

In Figures 72, 75 and 76 we have assumed that the generator is equipped with permanent magnets which create the magnetic field. This is the case for small magnetos, but for other generators this field is furnished by electromagnets energized by a **field winding** on soft iron cores, and direct current machines are classified by the different means adopted to energize or excite this field winding. A **"separately excited generator"**, with the standard convention for indicating it, is illustrated in Figure 77. It is so called because the direct current through the field winding is furnished by an external source, such as another generator or a storage battery.

A **"self-excited generator"** is the more common one and may be **shunt wound, series wound** or **compound wound.** The different methods of construction are shown schematically in Figure 78. As the E.M.F. induced in the armature is proportional to the magnetic field intensity, which in turn is proportional to the current in the field windings, a variation in the field current will cause a change in the armature E.M.F. With the shunt wound generator, an increase in load causes a decrease in field current, as may be seen from a study of parallel resistances, and consequently causes a decrease in armature E.M.F. On the other hand, in the case of the series wound generator, the armature E.M. F. increases with the load. The compound wound generator is designed to neutralize this change in armature E.M.F. by balancing the series effect against the shunt effect. An **over-compounded** generator is constructed with the series effect predominant so that the voltage increases slightly with change from no load to full load. Figure 79 shows curves representing armature voltage plotted against load for these various types of generators.

Generators may be further classified by the number of poles, a four-pole machine being represented by Figure 80. In every case there are the same number of brushes as poles, alternative brushes being connected together, as shown, to form the armature terminals. The voltage with four poles will be double that with two poles if the same armature winding and the same machine speed are used.

## 46. Battery Charging Machines for Telephone Offices

The principal use of direct current generators in telephone and telegraph work is for charging central office storage batteries. The essential requirements for a generator used for this purpose are as follows:

a. It should have a voltage approximately 30% in excess of the rated storage battery voltage.

b. It should be constructed so as to give the minimum room noise and minimum electrical noise due to slot or other harmonics.

c. It should have a voltage load curve which will not result in an appreciable decrease in the storage battery charging current with the gradual increase of storage battery voltage due to charging.

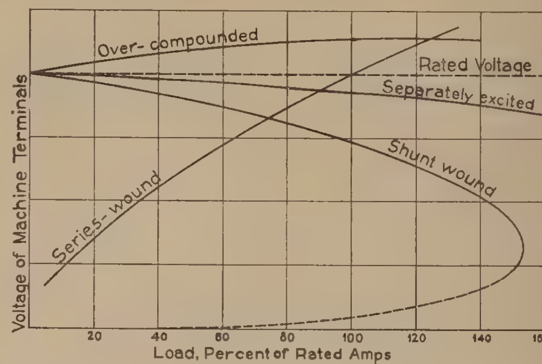



*Fig. 79—Characteristics of D. C. Generators.*

d. When installed, it should be equipped with suitable circuit breaking devices to open the charging circuit on either excess current or reverse current flow, which will prevent the storage battery from discharging through the armature of the generator or, in other words, prevent the generator from running as a motor.

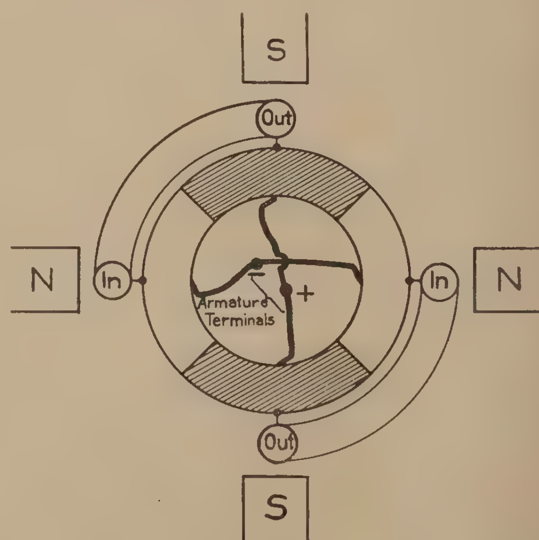



*Fig. 80—4 Pole, 4 Brush, 4 Segment D. C. Generator.*

e. If a single battery is used and is charged by a single generator the generator should have a kilowatt rating which will permit a current equal to the storage battery charging rate plus at least the maximum current required during the day by the central office.

TABLE V

| Type | M-1 | M-2 | M-3 | M-4 | M-5 | M-5 ½ | M-6 | M-8 | M-10 | M-15 |
|---|---|---|---|---|---|---|---|---|---|---|
| Amperes | 25 | 50 | 100 | 175 | 225 | 400 | 600 | 800 | 1000 | 1500 |
| K. W. | .75 | 1.50 | 3.00 | 5.25 | 6.75 | 12.0 | 18. | 24. | 30. | 45. |
| Efficiency | 60.0 | 69.5 | 74.0 | 77.2 | 78.5 | 81.2 | 83.4 | 84.8 | 85.0 | 85. |

Some of the characteristics of the various sizes of special generators used for charging 24-volt storage batteries are given in Table V.

Other generators are constructed by special design in accordance with Engineering Specifications. Commercial types of generators are also used when it is found practicable to suppress noise-producing harmonics normally present in their outputs by means of electrical filters.

The usual types of telephone generators are shunt wound. A study of the shunt curve in Figure 79 will show that this type complies with requirement "c" above, since the E.M.F. of the generator rises as the load decreases. These machines are very carefully designed to eliminate harmonics which would interfere with telephone circuits by causing objectionable noise.

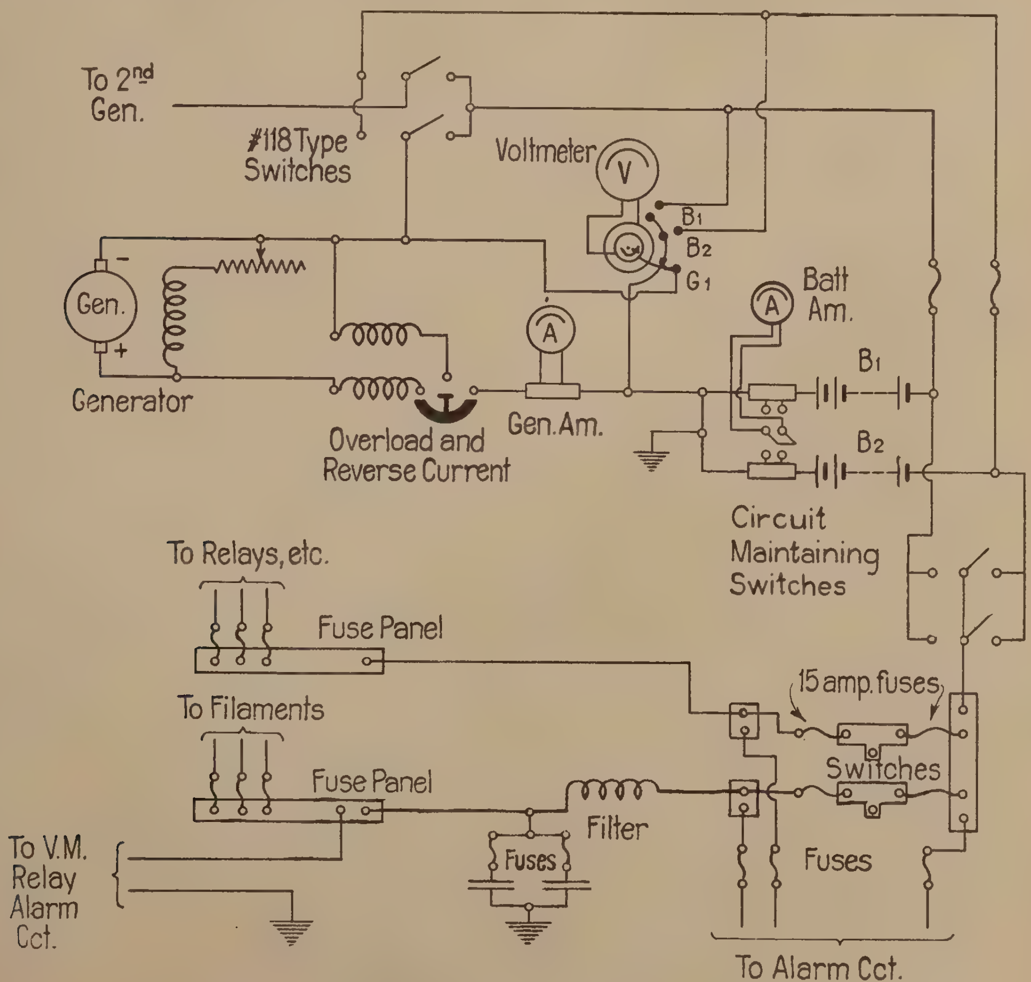



*Fig. 81—Typical Power Circuit.*

## 47. Typical Power Circuit for a Telephone Office

In accordance with the best practice in central office installations, the various parts of the power plant are often located in separate rooms. The storage battery is kept in a cool, well ventilated room in order to minimize the effect of the gas given off during charge. The power switchboard is usually located so that the operation of the generator may be watched while adjustments are made at the switchboard. The protective apparatus, ammeters, voltmeters, etc. are located on the switchboard. The fuse panels are a separately mounted unit of apparatus, usually close to the power switchboard.

Figure 81 gives a schematic arrangement for a typical power circuit. Although for simplicity only one generator is shown, it is standard to have two or more in a charging unit, so that any one of them may be used when switched into the circuit by means of the No. 118 type switches (single pole, double throw) shown near the generator. These switches permit either bank of storage batteries to be charged separately or any generator to be used on either battery. Similarly, the load may be thrown on either battery by means of the single pole circuit maintaining switches which control the flow of current to the fuse panel. A filter is inserted in the circuit to the filament supply panel in order to smooth out any possible variation in the current which might affect the more sensitive telephone apparatus supplied from this panel. One ammeter is inserted in the generator lead, another is arranged so that it may be placed in the lead to either battery, and a voltmeter is connected so that by means of a circular switch the E.M.F. of the generator or either battery may be read. Alarm circuits are arranged so that an appreciable change in voltage will ring a bell and notify the attendant.

## 48. Direct Current Motors

In the telephone plant, motors are used to drive charging generators, ringing machines and other minor units such as polishing machines and fans. These motors are ordinarily designed to operate on the city power distribution system, which may be either D.C., or A.C. There are many classes of motors as well as generators (series, shunt, compound, multi-polar) and each has different characteristics of power and speed. It is impossible to discuss particular types in this Course, and only a brief explanation of the fundamental working principle will be given.

When a conductor carrying an electric current is placed in a magnetic field at right angles to the lines of force, there will be a reaction between the circular field about the conductor and the field in which it has been placed. This reaction causes the lines of force set up by the two fields to aid or increase on one side of the conductor and to oppose or decrease in number on the other side which gives the conductor a tendency to move across the magnetic field in a direction depending on the direction of current flow in it.

If the conductor is a loop and is free to rotate, as in Figures 75-B, 76 and 77, illustrating D. C. generators, it will revolve as a motor. In fact **any D. C. generator may be used as a motor if the current flows into the armature and field instead of out of the armature.**

The direction of rotation may be determined by the **left-hand rule** which is similar to the right-hand rule (Figure 69) excepting that the left hand is used. The left thumb represents direction of motion; the forefinger direction of flux; and the middle finger direction of current flow.

When a motor is running, the armature conductors cut lines of force and an E.M.F., with a direction opposite to that of the applied E.M.F., is induced. This is called the **counter-electromotive force** and the current flowing in the armature will equal

$$I = \frac{E_i - E_c}{R} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

Where $E_i$ is the impressed E.M.F., $E_c$ is the counter E.M.F., and R is the armature resistance.

Since there is low counter E.M.F. until the motor has reached about its normal speed, it will draw a very large current at starting, unless this is prevented by a **starting rheostat** which is a variable resistance placed in series with the motor's armature and is gradually cut out as the motor is brought up to its proper speed. A starting rheostat of some type must be used for all large motors, but is sometimes not required for small machines, on account of their armatures having comparatively high resistances. The effect of this momentary overload on small motors is often evidenced by the blowing of fuses when the motor is started.

The following are a few simple rules which have practical application to the use of motors:

1. The direction of rotation of a D. C. motor may be reversed by reversing either the armature or field connections but **not** by reversing the supply leads.

2. The speed of a shunt wound motor may be adjusted by varying the field current. A **decrease** in field current gives an **increase** in speed and vice versa.

3. A series motor must either have an increasing load with increase in speed, such as a fan, or its operation guarded by an attended controller, otherwise it will "run away".

4. Motors must be kept dry and clean.

5. Commutators may be dressed with sandpaper but must never be dressed with emery cloth.

# CHAPTER VIII

## SOURCES OF DIRECT ELECTROMOTIVE FORCE IN THE TELEPHONE PLANT

### 49. Kinds of Sources of E.M.F.

For an electrical circuit to become energized, some source of electromotive force must be connected to it either by direct connection or through inductive relations. In the case of a **direct current**, the circuit must be energized by the actual connection of the conductors to the E.M.F. terminals, but in the case of an alternating current, the circuit may be energized either by such connection or by "inductive effects due to magnetic interlinkages or capacity relations".

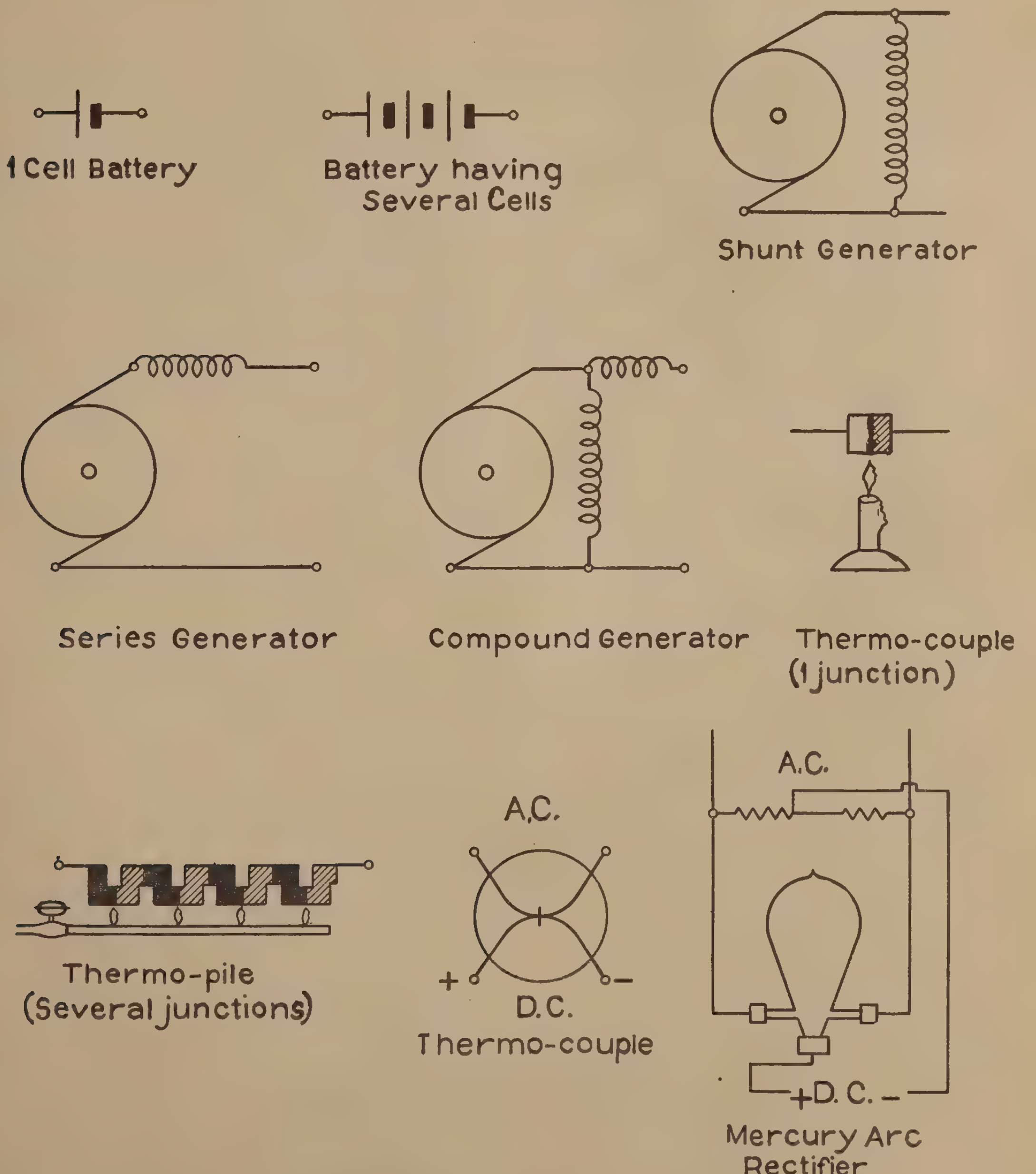



*Fig. 82—Circuit Conventions for Sources of Direct E. M. F.*

Primarily, if any device maintains an E.M.F. and sustains a current of electricity in a circuit, energy is supplied to the circuit. But the **law for conservation of energy** states **that energy cannot be created or destroyed. Any source of E.M.F.* may then be defined as a device for supplying electrical energy by converting it from some other form.** The battery directly converts chemical energy into electrical energy, the generator likewise converts mechanical energy into electrical energy, and the thermocouple directly changes heat to electrical energy. A rectifier in one sense is a source of direct E.M.F. but converts alternating current energy into direct current energy, changing it from one electrical form to the other rather than from some other form to the electrical.

Figure 82 shows the circuit conventions for sources of E.M.F. that are common in electrical work. In the operation of the telephone plant we are interested principally in the battery, the generator and the rectifier. The rectifier may be described only after the study of certain alternating current fundamentals. The theory of the generator was covered in Chapter VII. We may at this time discuss the various types of batteries and the general battery requirements of telephone service and make some mention of other interesting though perhaps less important sources of E.M.F.

### 50. Primary Batteries

Chemical batteries are divided into two classes, primary and secondary. A primary battery is one that generates an E.M.F. by virtue of certain chemicals coming in contact with submerged metals or other substances which constitute the positive

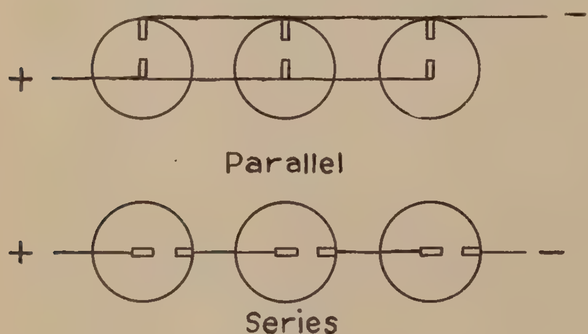



*Figure 83*

and negative terminals. A secondary battery stores electrical energy but does not directly generate an E.M.F. unless a current is first passed through the battery in a direction opposite to that in which it will flow when supplying energy to an external circuit.

*We have spoken of the battery throughout as a "source of E.M.F." It is equally proper and probably more common usage to speak of it as a source of current or energy, but "source of E.M.F." naturally suggests the application of Ohm's law for every circuit, thereby giving a more accurate conception of circuit relations.

The unit of a battery is the cell, consisting of a single couple of submerged positive and negative poles or plates. As illustrated in Figure 83, cells may be connected in parallel or in series, depending upon the value of the E.M.F. desired and the value of current to be sustained. If they are connected in series, the E.M.F.'s are added, making the total E.M.F. of the battery the sum of the E.M.F.'s of the individual cells. If they are connected in parallel, the E.M.F. of the battery is that of a single cell, but the current supplied to the circuit is divided between the several cells.

A battery may consist of groups of cells connected in parallel and these in turn connected in series, or vice versa. Figure 84 shows two methods of connecting six cells where the E.M.F. desired is that of only three cells and a single string is not sufficient to sustain the current required. Theoretically, the two methods give the same results, but in the case of dry cells, method "B" has some advantage from the standpoint of deterioration of the battery due to the uneven electrical characteristics of the individual cells.

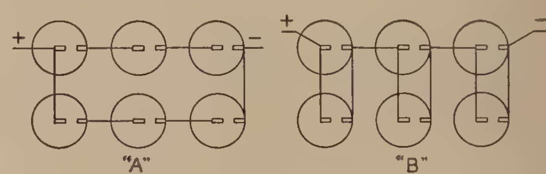



*Figure 84*

The various types of primary batteries may be divided into two general groups called "wet" cells and "dry" cells. The more common of the wet types are as follows:

a. The **Daniell cell** in its many forms, which consists of a zinc plate in a solution of zinc sulphate and a copper plate in a solution of copper sulphate (blue vitriol). Originally the two solutions were separated by a porous cup which contained one solution and was submerged in the other. One of the later and more commonly used types, called the "gravity cell", dispenses with the porous cup on account of the two solutions having different specific gravities. The copper sulphate, being heavier than the zinc sulphate, is placed in the bottom of the jar with a copper plate, and the zinc sulphate in the top of the jar with a zinc plate (or "crow's foot").

b. The **sal ammoniac cell,** which consists of a zinc negative rod or plate and a carbon positive plate in a solution of sal ammoniac (ammonium chloride).

c. The **Lalande cell,** which consists of a zinc negative cylinder in a solution of caustic soda and a perforated sheet iron cylinder in which is embodied black copper oxide. The two are separated by cylindrical insulators.

About the only **wet cell** used to any extent in the telephone plant is a special form of the Lalande cell known as the "Edison Primary Battery". It has a capacity of about 500 ampere hours and a very low internal resistance varying between .01 and .02 ohms. The voltage on an open circuit is a little more than .9 of a volt, and on a closed circuit between .6 and .7 of a volt for a discharge rate of 30 milliamperes.

The **dry cell** is a special form of chemical battery, so constructed that the chemicals used in its action are sealed. It is most convenient for shipping and general use. Neglecting the miniature types that are used mostly for flashlight batteries and vacuum tube grid and plate circuits, there are two important and general classes of service for which dry cells are designed. They may be constructed for heavy current duty, such as automobile ignition, at a sacrifice of life; or may be intended for connection to a high resistance and thus give a low current output. In the latter case, the cells do not require replacement for a much longer period, particularly if the service is required only at intervals and the battery is allowed to "rest" on open circuit, as in the case of transmitter supply on magneto telephones.

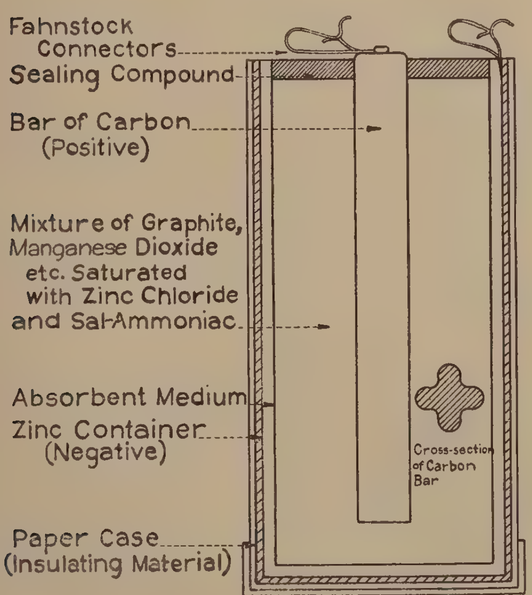



*Fig. 85—Cross-Section of Dry Cell.*

The Blue Bell dry cell, which is standard with this Company, is representative of the "long-life" type. Its construction is illustrated in Figure 85. Its negative terminal consists of a zinc container in which is centered a bar of carbon as a positive terminal. The carbon is surrounded by a porous medium consisting principally of graphite and manganese dioxide, and this mixture is saturated with a solution of zinc chloride and sal ammoniac. A layer of absorbent material similar to blotting paper separates the zinc from the mixture, but is porous to the liquid solution which generates an E.M.F. when it comes in contact with the zinc. The top of the cell is sealed with an insulating compound and a cardboard container acts as an insulating cover for the zinc. Fahnestock connectors, which are securely fastened to the zinc and carbon electrodes, form suitable terminals. When new, this dry cell gives a voltage of 1 to 1½ volts, which decreases with age, and has an internal resistance of .2 to .3 ohms, which increases with age. For average use, its capacity may be roughly estimated at 20 to 30 ampere hours but this will vary considerably depending upon conditions. For example, the capacity when connected to a high resistance circuit may be several times the capacity when connected to a low resistance circuit. Intermittent use is also an important factor.

Blue Bell dry cells are commonly used in the telephone plant for practically all service where connections to central office storage batteries are not feasible or cannot be used because the storage battery is grounded. In addition to transmitter batteries for magneto subscribers' stations, such uses include battery supply for telegraph sounders on subscribers' premises, Wheatstone bridge testing battery for toll testboards, plate batteries for vacuum tube circuits and testing batteries for portable testing sets. The more important maintenance requirements that are essential to their proper use may be summed up as follows:

a. Dry cells are ordinarily rejected from service when they will not sustain a current of .125 amperes through a resistance of 5 ohms for five seconds. This is called the "cut-off point" and the test is ordinarily made with a #36 Battery Gauge (watch case type).

b. On account of the limited capacity, if used in connection with circuits taking an appreciable current, some device should be installed for opening the circuit when it is not in use.

c. The cardboard covering which is used as the only insulating means between the various cells of a dry cell battery, must be kept free from moisture.

d. New dry cells should never be connected in parallel with old dry cells since the greater voltage of the new cell may be shunted to a degree by the old cell.

### 51. Storage Batteries

A chemical battery that is capable of storing electrical energy delivered to it from some other source, and delivering this energy to an electrical circuit at some later time is called a secondary battery. Other names commonly used are "accumulator" and "storage battery". The two general types of storage batteries are the "lead-acid-lead" and the Edison (iron-potassium hydroxide-nickel).

TABLE VI

| Standard "Chloride Accumulators" | | | |
|---|---|---|---|
| Type | Number of Plates | Size of Plates | Amperes per * Positive Plate |
| CT | 2 | 5 x 5 | 1½ |
| PT | 2 | 8¾ x 5 | 3 |
| ET | 2 | 7¾ x 7¾ | 4½ |
| D | 3-13 | 6 x 6 | 2½ |
| E | 5-15 | 7¾ x 7¾ | 5 |
| F | 9-27 | 11 x 10½ | 10 |
| G | 11-75 | 15-5/16 x 15-5/16 | 20 |
| H | 21-51 | 15-5/16 x 30-11/16 | 40 |

On account of its low internal resistance and more constant terminal voltage, the "lead-acid-lead" type more nearly meets the exacting requirements of the telephone central office. (These requirements are discussed in Article 52). This Company has standardized storage cells which are manufactured by the Electric Storage Battery Company of Philadelphia and sold under the trade name of "Chloride Accumulators", thus called from a now discontinued process of plate manufacture using chlorine.

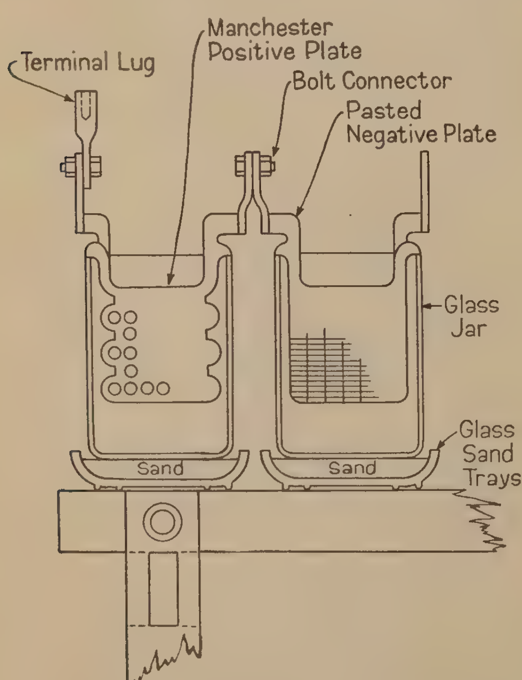



*Figure 86*

Table VI gives the standard sizes and rated capacities of "Chloride Accumulator" cells commonly used in telephone central offices. More complete tables are given in the Long Lines Department's Supply Catalogue. The essential parts of representative cells are shown in Figures 86 and 87.

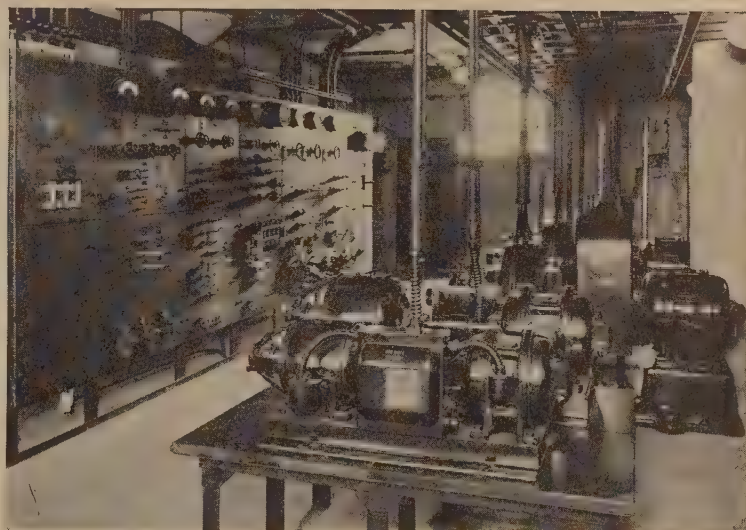
The complete chemical theory of a lead-acid-lead battery is not simple but the fundamental chemical action is briefly as follows: When the cell is in the charged condition, the active constituents are a positive element of lead peroxide ($Pb\ O_2$) and a negative element of spongy lead ($Pb$) in a dilute solution of sulphuric acid ($H_2\ SO_4 + H_2O$). When the battery is discharged, the current, passing from the positive to the negative plate through the external circuit, must return from the negative to the positive plate through the dilute acid (electrolyte) and in doing so, breaks the electrolyte into its component parts resulting in first, the spongy lead of the negative plate combining with the positively charged component ($SO_4$) of the electrolyte forming lead sulphate ($Pb\ SO_4$) and losing its negative charge; second, the oxygen of the lead peroxide of the positive plate combining with a part of the hydrogen liberated from the electrolyte, forming water, and converting the positive plate to pure lead; and third, a similar breaking up of the sulphuric acid at the positive plate forming more water and converting some of the lead of the positive plate into lead sulphate by the same chemical action that takes place at the negative plate.

When the storage battery is charged, the chemical action is reversed. The following chemical equation is used to explain the action of discharge when reading from left to right and the action of charge when reading from right to left

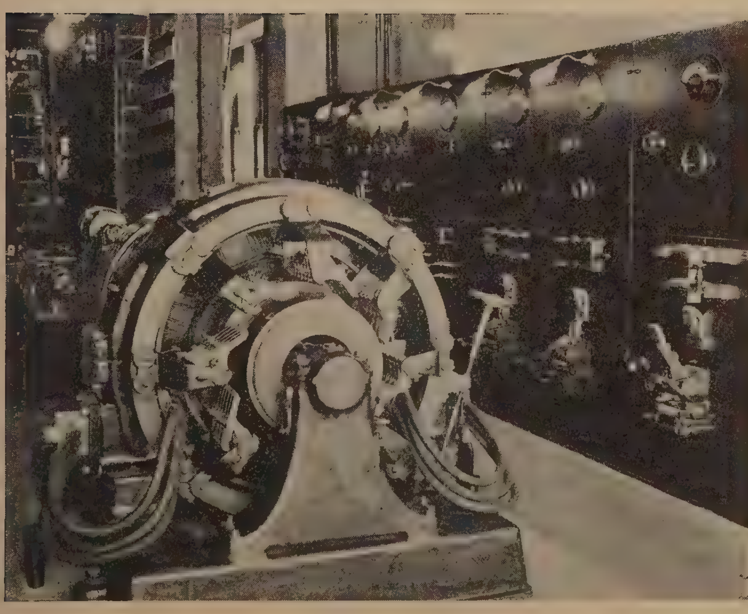
$$Pb\ O_2 + Pb + 2H_2\ SO_4 = 2\ Pb\ SO_4 + 2\ H_2O \quad (28)$$

*__Note__:—To find normal charging rate or 8-hour discharge rate for types D, E, F, G and H, take one less than the number of plates, divide by two, and multiply by "amperes per positive plate".

# TOLL POWER PLANT



*Above*—Storage battery room. Telegraph and telephone repeater batteries are mounted in the far end of the room and the much larger 24-volt batteries may be seen in the foreground.



*Above*—Battery charging machines and power switchboard in typical repeater station.

*Left* — Battery charging generator in large station. This machine delivers 1500 amperes D.C. at 24 volts.

In the practical operation of a storage battery, we must be able to determine the state of charge or discharge at any time and it is not convenient to do this by chemical analysis. But in the foregoing explanation of the cycle of charge and discharge, there are two changes taking place that may be easily determined. One is the change in the electrical charge held by the plates, resulting in a change in the E.M.F. of each cell; and the other is the increase on discharge, and the decrease on charge, in the amount of water contained in the electrolyte, which increase or decrease, as the case may be, changes the specific gravity of the electrolyte. This latter condition gives the better index to the cell's operation and is the one ordinarily used.

Figure 88 shows an hydrometer that is specially designed for determining the specific gravity of the electrolyte. A weight at the bottom makes the hydrometer float in an upright position and, according to the law of all floating bodies, the weight of the liquid displaced must be equal to the weight of the hydrometer. The scale is always read at the surface of the liquid and, naturally, the reading for denser liquids will be near the bottom end, while for lighter liquids, it will be near the top end. Pure sulphuric acid has a specific gravity of 1.8342 but the electrolyte used in storage cells is diluted down to approximately 1.200 with considerable variation according to the state of charge. The hydrometer reading must be corrected for temperature since a rise in the temperature of the electrolyte means an expansion of its volume and a lowering of its specific gravity. The basis for comparison of readings is taken as 70° F. Three degrees increase means a reduction of .001 in specific gravity and vice versa.

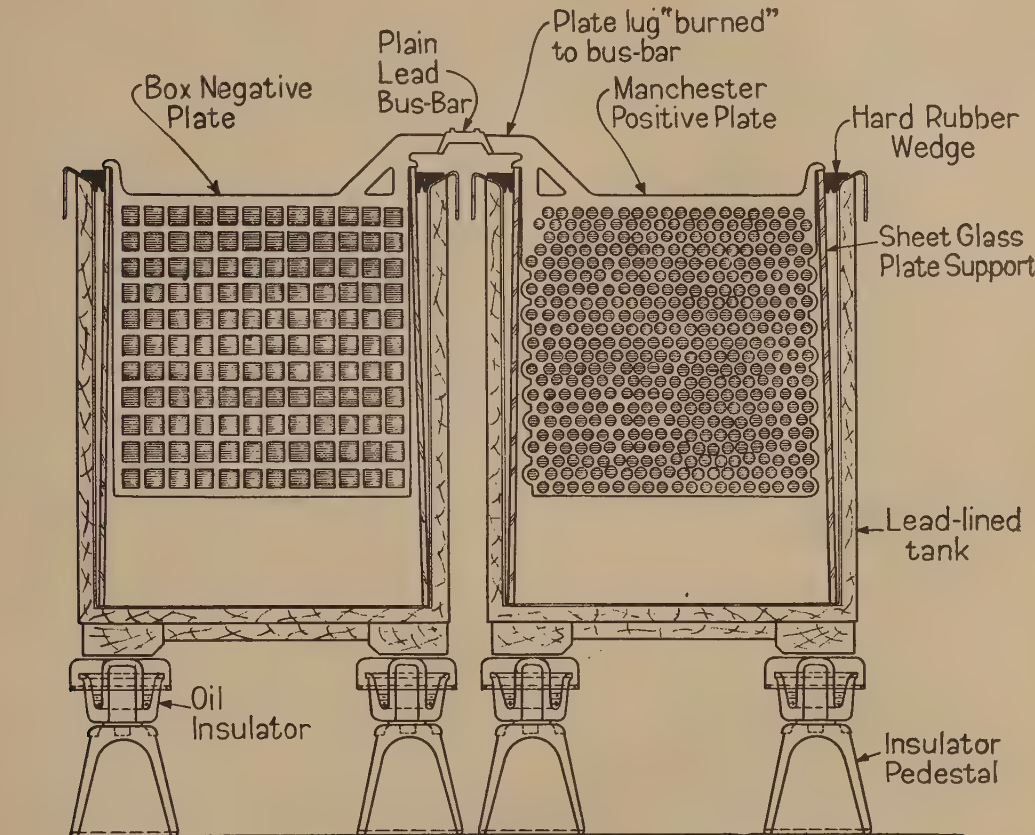



*Fig. 87—Type "G" Battery.*

Note:—The installation and maintenance of storage batteries is a specialized feature of telephone plant work and cannot be covered in this Course. In this connection it may be of interest to see Engineering Specifications No. 3750 which is issued in booklet form.

## 52. Some Power Plant Requirements in Telephone Offices

The telephone central office power plant must be not only absolutely reliable at all times but must meet other exacting requirements. Modern practice has led to the standardization of a common

source of E.M.F. for the majority of the talking circuits, as well as for the operation of telephone relays, telegraph sounders, vacuum tube filaments, small motors and numerous other apparatus units. We thus have a very general use of the standard 24 volt storage battery, with additional smaller batteries used for such services as 48 volt subscriber's

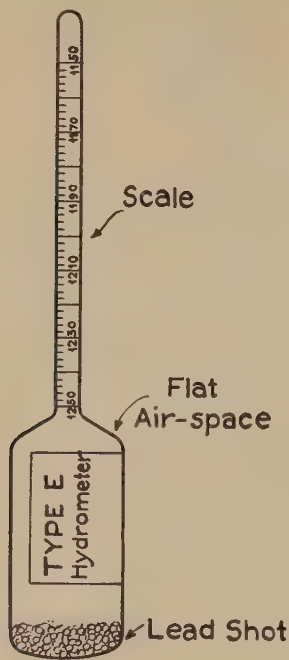



*Fig. 88—Hydrometer.*

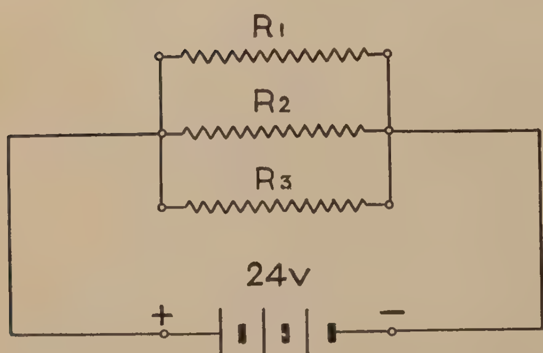



*Figure 89*

transmitter supply on long distance connections, 120 volt supply, both positive and negative, for telegraph repeater operation and other voltages for telephone repeater operation. The common battery results in a number of plant economies but, on the other hand, imposes certain exacting electrical requirements. Probably the most essential of these requirements is **low internal resistance.**

In our study of simple electrical circuits, we have considered a single source of E.M.F. for each individual circuit but we have learned that any number of resistances may be connected in parallel, as shown by Figure 89, and that the current in any single resistance is independent of that in any other resistance provided all resistance branches are connected directly to the terminals of the battery as indicated. This follows naturally from the application of Ohm's law to a single resistance branch, since the E.M.F. impressed on any single branch is the E.M.F. of the source and, theoretically, is independent of current flowing through other branches. This assumes, however, that the battery is a perfect source of E.M.F. without internal resistance.

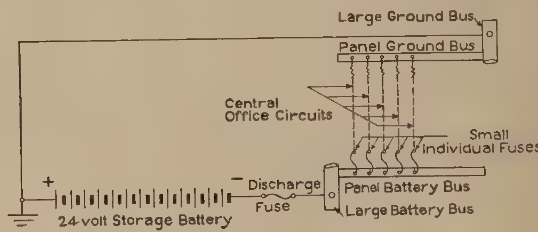



*Figure 90*

Figure 90 represents the central office storage battery connected to bus bars at the fuse panel. The central office circuits are cabled to this fuse panel and receive their battery supply through taps to the small panel busses. Thus hundreds of circuits of varying resistance are connected in parallel to a common battery, and we have in practice a circuit arrangement identical to that shown in theory by Figure 89, excepting that as indicated in Figure 90

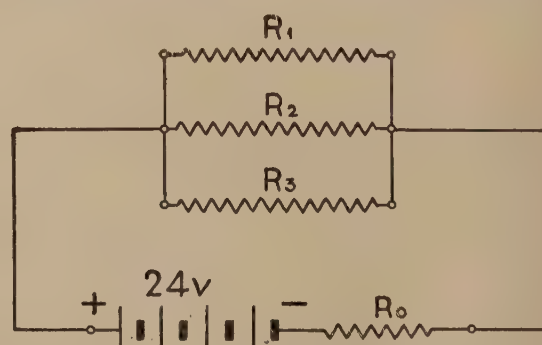



*Figure 91*

fuses for protection against excessive currents due to short circuit or overload are used and the positive terminal of the battery is connected to ground. This ground connection stabilizes the potential of all circuits in the central office by short circuiting their capacities to ground. It also simplifies the central office wiring and affords circuit protection, but it cannot in any way affect the total current supplied by the battery or the current in any individual circuit that may be connected to the bus bars.

Returning to Figure 89, in which the current in any one resistance branch was seen to be independent of that in any other (provided the source of E.M.F. is a perfect one), let us assume, on the contrary, that the battery has an internal resistance of $R_0$ and that the circuit is actually that shown by Figure 91. Due to the resistance $R_0$, the current in one branch is no longer independent of that in other branches. Let us assign values as follows:

$R_0 = 2$ ohms
$R_1 = 5$ ohms
$R_2 = 4$ ohms
$R_3 = 3$ ohms
$V = 24$ volts

If we solve this network, we shall find that the current through $R_1$ is 1.87 amperes. If we should suddenly open resistances $R_2$ and $R_3$, it will immediately change to 3.43 amperes. Applying the same principle to Figure 90, **unless the central office source of E.M.F. has negligible resistance, including both the internal resistance of the battery and that of the supply leads from the battery to the bus bars where individual circuit leads are connected, there will be everchanging current values in the individual circuits. This will result in noise and crosstalk in all talking circuits and unreliable operation of various other telephone apparatus.** From this it follows that common battery operation for any number of circuits may be substituted for local or individual batteries only when the common source of E.M.F. has negligible internal resistance.

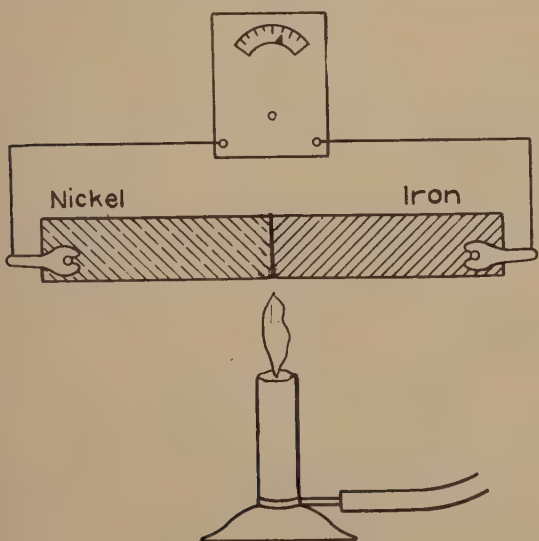



*Figure 92*

## 53. Thermocouples

The thermocouple is probably the simplest source of electromotive force but it has little practical use as a source of energy supply. Nevertheless, on account of being a direct means of establishing an electrical current from heat, its principle of operation is becoming increasingly important, and its simplicity permits its use in connection with certain electrical testing apparatus. It consists of two dissimilar metals in contact with heat applied to their junction. The different characteristics of the two metals results in a difference of potential between them when heat is applied to their junction, and if a galvanometer is connected as shown in Figure 92, current can be detected. Almost every combination of dissimilar metals will give the thermocouple effect, but some combinations are better than others. Bismuth and antimony, iron and constantin, copper and nickel are frequently used. For a single combination of any two metals, the E.M.F. generated

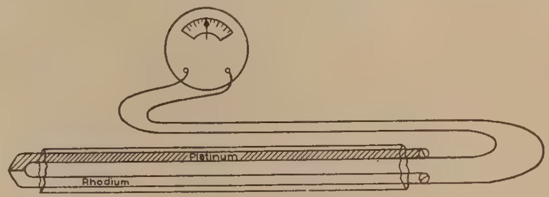



*Fig. 93—Pyrometer.*

is very low. A group of such metals is often connected in series, and such an arrangement is called a "thermopile". The thermocouple is used extensively in connection with converting a direct current measuring instrument to an alternating current measuring instrument that is independent of frequency. It also permits the measurement of temperatures much higher than can be measured with any thermometer.

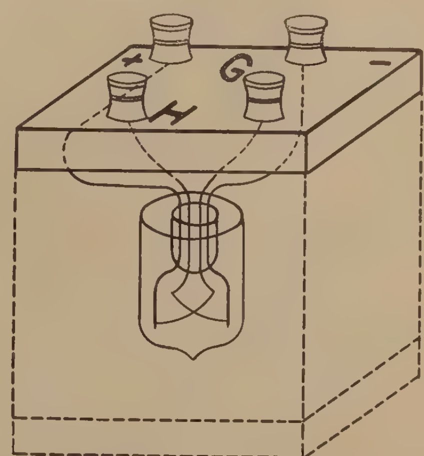



*Fig. 94—W. E. Co. Thermo-couple.*

Figure 93 illustrates an instrument known as the "pyrometer" which consists of a thermocouple on the end of a long rod that may be inserted through

an opening in a furnace wall. The temperature of the furnace is determined by means of a delicate electrical instrument connected to the thermocouple and calibrated for reading degrees of temperature instead of current values.

In the telephone plant, the thermocouple, of which there are a few standardized types, is used primarily as a device for measuring weak alternating currents. The A.C. circuit is connected to the heater terminals (marked "H", as shown in Figure 94) and heats the junction of dissimilar metals, thus giving rise to a small direct current. The D.C. terminals, marked "G", are connected to a D.C. galvanometer or milammeter which gives by its deflection a relative measure of the input A.C. or "heating" current. The Western Electric Company manufactures thermocouples for laboratory and general use, having the glass-enclosed element encased in a small wooden box, and others, for some special purposes such as carrier systems or transmission measuring sets, having the glass-enclosed element mounted in a cylindrical metal container equipped with either ordinary terminals or a vacuum tube base for use in 100-A sockets. For general use, there are three resistance values for the heater element, viz. 5 ohms, 40 ohms and 600 ohms.

## CHAPTER IX

## INDUCTANCE AND CAPACITY

### 54. Various Conditions of Current Flow

Thus far in this Course we have confined our attention largely to circuits of relatively simple characteristics. We have had a source of direct E.M.F. connected to one or more resistances and have assumed a steady flow of current through each closed branch. We have noted, however, the alternating character of the E.M.F. generated by a closed loop revolving in a magnetic field but we have not attempted to analyze the behavior of such an E.M.F. when acting on various types of circuits.

It is desirable at this time that we broaden out our studies somewhat to include more general conditions and while nothing that we have learned thus far will be invalidated, it will be necessary for us to study certain additional properties of electrical circuits and their effect on the various conditions of current flow.

Broadly speaking, the study of current flow may be divided into five parts, classified according to the following:

a. That flow which results from a constant direct source of E.M.F. connected to a direct current network (i.e., the condition assumed in the earlier Chapters of this Course for the calculation of direct current networks through the application of Ohm's and Kirchoff's laws).

b. The current flow resulting immediately after opening or closing the circuit, varying its resistance, or in some way interrupting the steady direct current flow for a short period of time during which the current values readjust themselves before again becoming fixed or steady.

c. Current flow where the source of E.M.F. is an alternating one, having the simplest, most common and most convenient wave form, viz. the sine wave.

d. Current flow, where the source of E.M.F. is an alternating one having a definite wave shape other than the sine wave.

e. Alternating current flow immediately after opening or closing the circuit, or immediately after effecting some other change in circuit conditions.

We can further classify the conditions of current flow in the foregoing. Conditions **a, c,** and **d** are those relating to **"steady state"** currents, while **b** and **e** refer to temporary currents, sometimes called **"transients".** In practice we are mostly interested in steady state currents in so far as the actual determination of current values is concerned, but under certain conditions the effects of transients are important. Certainly, in a telephone connection we are concerned with any "clicks" or "scratches" that may be heard in a telephone receiver due to the opening or closing of circuits which are electrically connected to the telephone system. For example, when sending telegraph signals over a superposed telegraph circuit, there should be no appreciable "thump" in the telephone circuit, and the successful operation of both the telephone and the telegraph circuits introduces certain apparatus features having to do with changes in current values.

In fact we deal with all five of the circuit conditions mentioned above in the telephone plant. Let us consider a long distance line wire not only composited for telegraph service but having a carrier current telegraph channel. The resulting current in the wire can best be studied by scrutinizing the behavior of its separate components. When analyzed, the current due to the composited telegraph connection alone is an illustration of two of the circuit conditions, namely **a** and **b.** At the instant of "make" or "break" of the key, conditions are as described by **b.** When the key is closed, i.e., when signals are not being sent, conditions are as described by **a.** For the carrier channel we likewise have condition **c** for a part of the closed key period and condition **e** for the instants of "make" and "break". For the main talking circuit, we have an application of **d** when a vowel sound is being transmitted, and an application of **e** when a consonant sound is being transmitted.

Thus we find in the telephone plant no scarcity of applications for every condition of current flow. It happens, however, that some of these are by no means simple and for practical telephone work we may limit our study to a thorough analysis of current flow for "steady state" currents only and to concepts, rather than calculations, of "transients" in either direct or alternating current circuits.

### 55. Changes in Direct Current Values

We may analyze condition **b** (changes in direct current values) since this will lead us to certain of the new circuit properties that we wish to examine. In Figure 95, with the switch open we have a circuit with infinite resistance and zero current flow; with the switch closed we have, by Ohm's law, a current—

$$I = \frac{E}{R} = \frac{10}{5} = 2 \text{ amperes.}$$

In spite of the apparent promptness with which electricity responds to the operation of any controlling device, we cannot conceive of the current changing from zero to two amperes without going

through the range of every intermediate value between zero and two amperes; neither can we conceive of the current building up in the circuit in zero time to the value given by the application of Ohm's law. If such were the case the current would have every value from 0 to 2 amperes at the instant of closing the circuit. Reverting to our water analogy with the circulating mechanism in Figure 2, when a valve is shut we know there is no flow of water in a long pipe line and when the valve is opened we know that, due to the inertia of the water, a definite time is required for the flow to become a maximum. A current in an electrical circuit cannot be established instantaneously any more than the water flow can be established instantaneously.

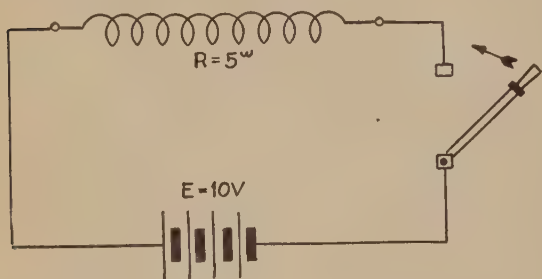



*Fig. 95—Simple Circuit With Inductance.*

Again, if in Figure 95 we suddenly open the switch in a dark room while there is a flow of two amperes in the circuit, we shall observe a spark at the contacts of the switch. Though the electrical current is reducing in value, it continues to flow for an instant after the switch points are no longer in contact, forcing itself through the air, and thereby forming an "electrical arc" which gives the illumination.

We thus have two conditions of current flow where the current in a brief interval of time assumes all intermediate values from two amperes to zero and we can associate these with other less abrupt changes in a circuit, such as those due to a varying transmitter resistance which causes varying current values. It may be said that an electrical circuit "reacts" to such current changes. But this reaction cannot be explained by our previous understanding of either resistance or E.M.F. The circuit has other properties which are latent when the current flow is a steady unidirectional one without change in value but which are immediately brought into play when the current attempts to change its value. There are two such additional properties, namely **"inductance"** and **"capacity". Inductance tends to give the circuit something that is analogous to inertia in a mechanical device, and capacity something analogous to elasticity.**

## 56. Inductance

When an E.M.F. is connected to a circuit, the conditions are somewhat analogous to those obtaining when a locomotive starts a train. The locomotive exerts considerable force which in the circuit corresponds to the impressed E.M.F. A part of this force is used in overcoming any resisting forces, such as the friction of the moving wheels, the grade of the track and others that apply to the train as a definite resistance to its motion at all times. The second part of the force is used in setting the train in motion, i.e. accelerating the heavy inert body. As soon as the train is accelerated to full speed, the entire force applied is available for overcoming the resistance alone. Likewise in the electrical circuit for any given E.M.F., current does not instantaneously establish itself to that value which represents the effect of the full voltage overcoming the resistance.

We have learned that there is a magnetic field about every current-carrying conductor, and when a conductor is wound into a coil or is in the presence of iron the magnetic field is intensified. The magnetic field cannot be established instantaneously any more than the train can suddenly be changed from its state of rest to that of full speed. What actually happens in the case of the electrical circuit is that the E.M.F. endeavors to start a current; the current in turn must establish a magnetic field;—this field reacts upon the circuit in a manner similar to that in which the counter E.M.F. generated by

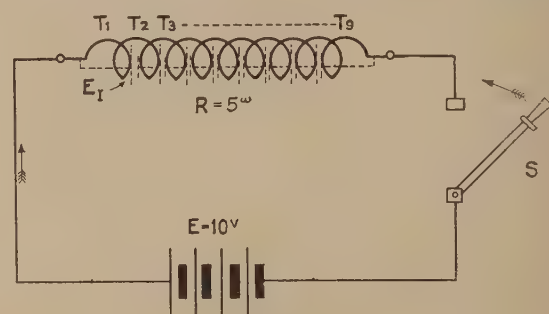



*Figure 96*

a motor opposes the terminal voltage and for an instant a part of the E.M.F. that is connected to the circuit must be used in overcoming these reactions. The current, therefore, increases gradually and as it does so, the magnetic field becomes more nearly established and the reaction becomes less pronounced, until finally the entire E.M.F. is applied to overcoming the resistance of the circuit alone, thereby sustaining the established current at a value determined by Ohm's law.

This may be more clearly understood by referring to the circuit shown in Figure 96 and following the change in current that is taking place immediately after the switch has been closed. This is represented by the curve in Figure 97. When the switch **S** is closed the E.M.F. **E** endeavors to establish a current in the circuit equal in value to E/R or two amperes. But the current, as has been stated, must go through every intermediate value

from zero to two amperes. By directing our attention to only one turn of the coil, for example, $T_1$ we can imagine the current building up, and in consequence establishing lines of force around this single turn which will, however, cut each additional turn of the coil. This action will set up in the other turns an induced E.M.F. tending to make a current flow in the opposite direction in much the same way as we learned a back E.M.F. was set up in the electric motor. And as in the case of the motor **the two currents are in one and the same circuit** and the induced current is opposed to the current established by virtue of the battery E.M.F. Figure 97 represents graphically the current in this circuit. With the switch open, the current is zero.

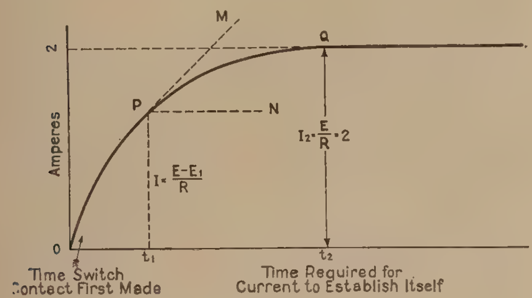



*Fig. 97—Curve for Rising Current.*

When it is closed (or when sufficiently near the contacts for the E.M.F. to break down the insulation of the narrow separation of air, since the current starts to flow before actual contact is made) the 10-volt battery will attempt to establish a current of two amperes in accordance with Ohm's law. But the current cannot be completely established until after an interval of time represented by $t_2$; and at the start it cannot be increasing at a rate greater than **that which would induce a back E.M.F. of 10 volts,** because if it did so, the induced E.M.F. would be equal to the connected E.M.F. and since they oppose each other there would be no current whatsoever. As would be expected, however, the maximum rate of increase of the current occurs at the instant the switch is closed.

Now let us consider the conditions at some intermediate time between the closing of the switch and $t_2$. If from the value represented by point P the current increased at a rate that continued without changing, the line PM would represent the trend of current values which would follow. But with the current increasing at this rate, the lines of force are cutting other turns of wire and inducing an E.M.F. which we might represent in Figure 96 as a second battery $E_1$, and which must be of the value necessary to establish a current equal to two amperes **minus the current which has been already established at the point P.** This follows from the earlier explanation regarding the directional property of an induced E.M.F. If the battery voltage E acted alone, the current value would be E/R or two amperes. Since the actual current flowing is less than two amperes, the difference between the actual current and two amperes may be regarded as due to a current flowing in a direction opposite to that of the two amperes set up by the battery. This current is established by the induced E.M.F. and we may designate it as an **induced** current to distinguish it from the two-ampere current which the supply voltage tends to set up. The actual current in the circuit, at any instant then, is the numerical difference between the two-ampere battery current and the induced current.

If we now assume for the sake of reasoning that the induced voltage $E_1$ remains unchanged, the resulting induced current will oppose the battery current, and the net amount of current flow will remain at the value P. We know, however, that the current which will eventually flow is two amperes, and furthermore if the current becomes constant at a value P, no lines of force are in motion; hence there is no induced voltage and consequently no induced current. But with no induced current, the battery will set up two amperes; therefore our assumption that the induced voltage $E_1$ remains constant, keeping the current down to a value such as that represented by the line PN, is false. On the other hand it is clear that the induced voltage $E_1$ cannot become zero until the current becomes two amperes though it does continue to decrease in value since we know that a current is always accompanied by a magnetic field which must change if the current changes and the result of such a change is an induced voltage. From this we conclude that there must be a compromise trend for the curve of current as it establishes itself, somewhere between the two extremes. This compromise is that shown by the curve PQ which is tangent to but bending away from PM. The current is neither maintaining the same rate of change as it approaches the value fixed by Ohm's law nor does it cease entirely its increase in value before it reaches two amperes, because while the induced E.M.F. that would stop the change in current is gradually becoming less in value the IR drop is becoming greater, and the sum of these two must always equal the impressed voltage in accordance with Kirchoff's second law. Thus we see from the curve in Figure 97 the "choking" effect of an inductively wound coil to **increases in current value.**

The case of a decreasing current value and the E.M.F. induced at the time of **opening** a circuit is of course another application of the same theory but the effects are different in their practical aspects. Because this E.M.F. is induced as a result of a **decreasing** current instead of an increasing one it **aids instead of opposes** the existing E.M.F. Moreover on account of the current change being a very rapid one due to the opening of the switch tending to change the resistance of the circuit from a definite value to infinity with great suddenness, the induced E.M.F. may become even greater than the existing E.M.F. besides being additive to it, whereas in the closed circuit it can never be greater than

the existing E.M.F. This total E.M.F. of the opening circuit tends to force an arc across the switch contacts which is greater than the arc at the time of closing the switch because the voltage is greater. Here we have the analogy of inertia where we attempt to stop suddenly a moving body whereas before the analogy covered starting a body from a state of rest.

Briefly, Ohm's law holds at all times, but the property of inductance in a circuit may cause the establishment of an E.M.F. opposing that connected to the circuit in the case of an increasing current, or aiding that connected in the case of a decreasing current. The value of this induced E. M.F. is not necessarily a fixed one; it varies, and either in the case of a current establishing itself or in the case of a current decaying, eventually becomes zero. The magnitude or influence of the induced E.M.F. as a reactive effect is determined by two factors:

a. The first is a **property** of the circuit having to do with the **number of inductive turns, whether or not each coil has a magnetic core and if magnetic,** the **permeability of the iron,** etc.

b. The second is the **rate of change of current.** This employs the **property** of the circuit as a tool or facility for creating the induced E.M.F.

The **property of the circuit** which we have called **inductance** is represented by the symbol L and is measured in units called "Henrys". The **rate of change in current,** though a varying quantity, would naturally be measured in amperes per second or I/t. (In this case I/t represents the rate of change of current which if maintained constant, would permit the current to rise from a value 0 to a value I in a time interval t.) The value of **the Henry is taken as the inductance of a circuit that will cause an induced E.M.F. of one volt to be set up in the circuit when the current is changing at the rate of one ampere per second** from which we may write

$$E_I = \frac{LI}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

where $E_I$ is the chosen symbol for induced E.M.F. and L represents inductance in henrys.

Since L depends upon a property of the circuit which has to do with **conductors cutting lines of force,** it can be defined in other terms. In Chapter VII we learned that one volt was established in a conductor that cut 100,000,000 lines of force per second. It follows that in a circuit having an inductance of one Henry 100,000,000 lines of force will be cut for each **ampere per second** change in current value. Here it should be noted that in this case the lines of force are moving and the conductors are stationary; the effect is of course the same as in the reverse case where the conductors are moving and the lines are stationary. Considering the inductance of any given coil, the lines of force or flux threading through the coil as they build up or decrease will cut each turn or we may write—

$$E_I = \frac{\Theta\ N}{100{,}000{,}000 \times t} \quad \ldots\ldots\ldots\ldots \quad (30)$$

where $\Theta$ is the flux through the coil, N is the number of turns and t is the number of seconds required for the flux to cut the turns. But, from equation (29), $E_I = \frac{LI}{t}$; therefore, $\frac{LI}{t}$ can be substituted for $E_I$ in equation (30) and we have

$$\frac{LI}{t} = \frac{\Theta\ N}{100{,}000{,}000 \times t} \quad \ldots\ldots\ldots\ldots \quad (31)$$

or with the t cancelled on both sides of the equation,

$$LI = \frac{\Theta\ N}{100{,}000{,}000} \quad \ldots\ldots\ldots\ldots\ldots \quad (32)$$

But in equation (13) we learned that $\Theta = M/R$ where M is magnetomotive force and $R$ is reluctance. Also, in equation (16) we found that for a solenoid M = 1.26 NI.

Therefore,

$$\Theta = M/R = \frac{1.26\ NI}{R} \quad \ldots\ldots\ldots\ldots \quad (33)$$

which may be substituted in equation (32) giving

$$LI = \frac{1.26\ NI}{R} \times \frac{N}{100{,}000{,}000}$$

$$L = \frac{1.26\ N^2}{R \times 100{,}000{,}000} \quad \ldots\ldots\ldots\ldots \quad (34)$$

The reluctance for any entire coil is determined by the dimensions of the coil and the permeability of the iron core and we may substitute in equation (33) an expression for reluctance (that follows from Equations 13, 16 and 17); i. e., $R = \frac{1}{\mu A}$

where $\mu$ is the permeability, 1 is the length of the core in centimeters and A is the area of the core in square centimeters.

Thus, we have finally

$$L = \frac{1.26\ N^2\ \mu\ A}{100{,}000{,}000 \times 1} \quad \ldots\ldots\ldots\ldots \quad (35)$$

**Note:**—This equation is theoretical rather than practical on account of coils in practice not conforming to the single long solenoid construction with a solid core. A study of Table VII together with judgment will give a better appreciation of inductance values, and methods of measurement that will be given later are to be depended upon in preference to equation (35).

TABLE VII

APPROXIMATE INDUCTANCE VALUES FOR WINDINGS OF VARIOUS ELECTRICAL APPARATUS

| Apparatus | | D.C. Res. (Ohms) | Impedance Components | | Conditions Under Which Measured | | | Inductance (Henrys) (See Note 2) |
|---|---|---|---|---|---|---|---|---|
| Name | Code No. | | A.C. Resistance (Ohms) (See Note 1) | Reactance (Ohms) (See Note 1) | Connections | Current | Freq'cy | |
| Relays, A.C. Types | 196-A | 3200 | 64300 | 293900 | Windings in series | .004 | 900 | 52. |
| " " | 87-A | 700 | 14000 | 15260 | | .003 | 900 | 2.7 |
| " " | J-1 | 1090 | 2400 | 4647 | | .004 | 20 | 37. |
| " " | 150-E | 234 | 450 | 678 | Armature held stationery | .009 | 135 | .8 |
| Relays, Telegraph | 21-A, 22-A, 23-A, 24-A, | 100 | — | — | — | — | 16 | 1 to 1.5 |
| " " | 25-A | 120 | — | — | | — | | 1 to 1.5 |
| " " | 30-A | 400 | — | — | Windings in series | — | | 3 to 4 |
| Sounders, Telegraph | 3-B, 4-A, 5-A | 20 | 60 | — | | — | | .28 to .51 |
| Receivers | 122 | 80 | 185 | 178 | Diaphragm vibrating | Normal | 800 | .036 |
| " | 144 | 80 | 140 | 165 | " " | Normal | 800 | .033 |
| " | 128 | 80 | 188 | 179 | " " | Normal | 800 | .036 |
| " | 528 | 80 | 125 | 225 | " " | Normal | 800 | .045 |
| " | 157 | 600 | 1380 | 1400 | " " | Normal | 800 | .280 |
| Retardation Coils | 12-A | 165 | — | 5024 | | Normal | 800 | 1. |
| " " | 47-B | 150 | — | | | | | .3 |
| " " | 5-AA | 74 | — | — | Two windings as connected for one wire | — | 16 | 2.7 |
| " " | 5-U | 500 | | | Single winding as in set | — | 16 | 3 to 4 |
| | | 1000 | | | Series aiding | — | 16 | 12 to 15 |
| " " | 44-B | 406 | 3000 | 61270 | Windings in series | | 900 | 11. |
| " " | 44-D | 166 | 2480 | 39565 | Windings in series | — | 900 | 7. |
| " " | 57-B | 350 | 1620 | 22610 | Windings in parallel | — | 900 | 4. |
| C.B. Subset | — | 64 | 509 | 281 | Transmitter replaced with 50-ω resistance | Normal | 800 | .056 |
| " " Ringer | 38-A | 1000 | 15300 | 18000 | | — | 900 | 3.2 |
| Loading Coils | 550 | Loop 3 | 5.2 | — | | — | 800 | .246 |
| " " | 549 | Lp px 1.2 | 2.9 | — | | — | 800 | .150 |

**Note:** (1) Impedance and impedance components will be discussed in Chapter XV. A.C. Resistance or the resistance component of impedance is often widely different from the resistance to direct current flow.

(2) Inductance values vary greatly depending upon conditions under which apparatus is operated, age of iron, degree of saturation, etc. This table gives only representative and approximate values.

If it is desired **to find the total inductance of a circuit having several coils in series, the inductances should be added in the same way that resistances in series are added. Similarly parallel inductances are calculated by the same formulas as are parallel resistances.** For example, see equation (4) and substitute L, $L_1$, and $L_2$ for R, $R_1$ and $R_2$, respectively, etc.

This property of a circuit which creates an E.M.F. from a change of direct current values when the reaction effects are wholly within the circuit itself is called "self-inductance" to distinguish it from the relation permitting electromagnetic induction between coils or conductors of separate circuits. This latter property of the two circuits taken jointly is called "mutual inductance". It will be discussed in a later Chapter.

## 57. Capacity

There remains that property of the circuit which we have called "capacity" that gives it something analogous to "elasticity". While a storage battery stores electricity as another form of energy, in a smaller way a **condenser** stores electricity in its natural state.

As a container a condenser is hardly analogous to a vessel that may be filled with water but more nearly analogous to a closed tank filled with compressed air. The quantity of air, since air is elastic, depends upon the pressure as well as the size or capacity of the tank. If the condenser is connected

*Figure 98*

to a direct source of E.M.F. through a switch (as shown by Figure 98) and the switch is suddenly closed there will be a rush of current in the circuit which will charge the condenser to a potential equal to that of the battery, but this current will be a decaying one and will become zero when the condenser is fully charged.

Even the insulated conductors of every circuit have to a degree this property of capacity, and a certain quantity of electricity representing a certain quantity of energy is delivered to a circuit before the actual transfer or transmission of energy from a sending device to a receiving device takes place. The capacity of two parallel line or cable conductors of considerable length is appreciable in practice.

The quantity of electricity stored by a condenser depends upon the condenser's capacity and the electromotive force impressed across its terminals. The following equation expresses the exact relation:

$$Q = E\,C \qquad (36)$$

where Q is the quantity of electricity in coulombs, E is the impressed E.M.F. in volts and C is the capacity of the condenser in **farads.** The farad is a very large unit and is seldom used in practice. The microfarad (from "micro", meaning $\frac{1}{1{,}000{,}000}$) is the practical unit more commonly used and with C expressed in these units, equation (36) becomes

$$Q = \frac{E\,C}{1{,}000{,}000} \qquad (37)$$

Figure 99 illustrates a condenser in its simplest form together with one convention used for a condenser connected to a battery. Two wires are connected to two parallel metal plates having a defin-

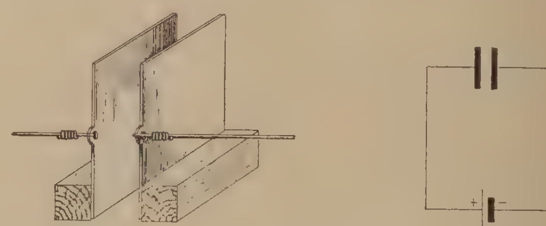


*Figure 99*

ite separation as shown. This is called an "air condenser" on account of air being the "dielectric" medium between the plates. The capacity of such a condenser is directly proportional to the area of the plates and inversely proportional to their separation. At the instant a battery is connected to its terminals, there is a rush of electricity which charges the plates to the potential of the battery, but as the plates become fully charged, the current in the connecting conductors becomes zero. Were we to insert a sensitive high resistance galvanometer in series with the battery, we would observe an instantaneous "kick" of the needle when the connection is made, but the needle would return and come to rest at zero. If the capacity of the condenser were increased, the kick would become more noticeable. If now the battery were disconnected and the condenser short-circuited through the galvanometer, there would be a kick of the needle in the opposite direction due to the quantity of electricity which had been stored on the condenser plates establishing an instantaneous current in the opposite direction and discharging the condenser through the winding of the galvanometer.

In addition to the size of its plates and their separation the capacity of a condenser depends upon the insulating medium between the plates. For example, if mica is inserted between the plates of an

## TABLE VIII

| DIELECTRIC POWER OF VARIOUS INSULATING MATERIALS (Values are only approximate and are given for value of K in equation (38) rather than compared to air as unity) | |
|---|---|
| Substance | K in Equation (38) |
| Glass—Very dense flint | $.9 \div 10^6$ approx. |
| Mica | $(.3 \text{ to } .7) \div 10^6$ " |
| Glass, ordinary | $.3 \div 10^6$ " |
| Shellac | $.3 \div 10^6$ " |
| Gutta Percha | $(.2 \text{ to } .4) \div 10^6$ " |
| India Rubber | $.2 \div 10^6$ " |
| Paraffin paper | $(.2 \text{ to } .3) \div 10^6$ " |
| Air (at atmospheric pressure) | $.0885 \div 10^6$ standard |

air condenser its capacity is increased about five times. The insulators in addition to being classified in the order of their insulating properties as given in Table III are classified in the order of their "dielectric powers", or **"specific inductive capacities"**, i.e., their ability to increase the capacity of a condenser over that of an air condenser as given in Table VIII.

The equation for a two-plate condenser is—

$$C = K \frac{A}{d} \quad \text{.......................} \quad (38)$$

where C is capacity in microfarads, K is the value of the constant taken from Table VIII, A is inside area of plates in square centimeters and d is separation of plates in centimeters. There are similar equations for calculating the capacity per unit length of parallel line conductors or cable conductors. These may be found in various electrical handbooks, but for telephone and telegraph work tables giving actual values, which vary for each class of line wires or cable pairs, are preferable and are usually available.

*Fig. 100—Condensers in Parallel*

An inspection of equation (38) will show that if two **identical** condensers are connected in parallel as shown by Figure 100 the effect is identical to doubling the plate area of a single condenser and therefore doubling the capacity. On the other hand if two identical condensers are connected in series as shown by Figure 101 the middle or common plates have a neutral potential and the effect is that of doubling the thickness of the dielectric of a single condenser, which cuts the capacity in half. It follows that capacities in parallel and series act inversely to resistances in parallel and series. This may be stated in a single rule covering all conditions:

> **Capacities in parallel should be added to find the total capacity in the same way that resistances in series should be added to find the total resistance and the reciprocal of the sum of the reciprocals must be taken to find the total capacity of capacities in series in the same way that the reciprocal of the sum of the reciprocals must be taken to find the total resistance of resistances in parallel.**

*Fig. 101—Condensers in Series.*

This rule may be expressed by two simple equations:

For several parallel capacities—

$$C = C_1 + C_2 + C_3 \text{ etc.} \quad \text{............} \quad (39)$$

For several series capacities—

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \text{ etc.} \quad \text{..........} \quad (40)$$

Or for only **two** series capacities a third equation may be expressed as follows:

$$C = \frac{C_1 \times C_2}{C_1 + C_2} \qquad (41)$$

**Note:**—Equation (39) may be compared with equation (4) and equation (41) may be compared with equation (8).

### 58. Effects of Inductance and Capacity in Direct Current Circuits

The circuit reactions coming from the presence of inductance and capacity offer their clearest applications in alternating current circuits when we deal with their effects singly or jointly as "reactance", a quantity to be measured in ohms as resistance is measured in ohms. On the other hand direct current applications in telephone and telegraph work are nevertheless common and Figure 102 shows one way to apply the property of capacity, to neutralize the detrimental effects of the self-inductance that is always present where there is a relay winding. Here the key contacts are bridged with a condenser which prevents excessive arcing when the circuit is opened because the sustained current is charging the condenser instead of forcing an arc. In practice the condenser usually has a non-inductive resistance in series, its purpose being to avoid oscillatory effects which will be discussed in a later Chapter.

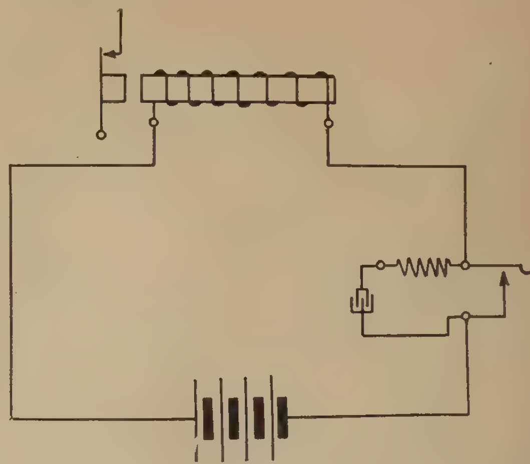


*Fig. 102—Condenser Connection to Reduce Sparking of Contacts.*

There are numerous other applications, perhaps the most outstanding one of which is the ordinary telegraph system with its many types of repeaters and other telegraph apparatus.

# CHAPTER X

## PRINCIPLE OF THE TELEPHONE

### 59. Sound

The telephone accomplishes the electrical transmission of speech by employing the mechanical energy of the speaker's voice to produce electrical energy having similar characteristics, and in turn converting this electrical energy into sound waves having similar characteristics at the listener's station. To understand its principle of operation we may well consider the nature of "sound".

Sound in the scientific sense has two distinct meanings. To the psychologist it means a sensation, to the physicist it means an atmospheric disturbance or a stimulus whereby a sensation is produced in the human ear. In other words, it is a form of wave motion produced by some vibrating body such as a bell, tuning fork, the human vocal cords or similar objects capable of producing rapid to and fro or vibratory motion.

Every one is familiar with the series of waves that emanate from a stone cast upon the still water of a lake or pond. This is one of many forms of wave motion and in a manner similar to that in which the stone coming in contact with the water establishes radiating rings formed by circular wave crests alternating with wave troughs, there emanates from a source of sound alternate condensations and rarefactions of the air. Instead of being rings on a single plane or surface, however, they are a series of concentric spheres expanding at a definite rate

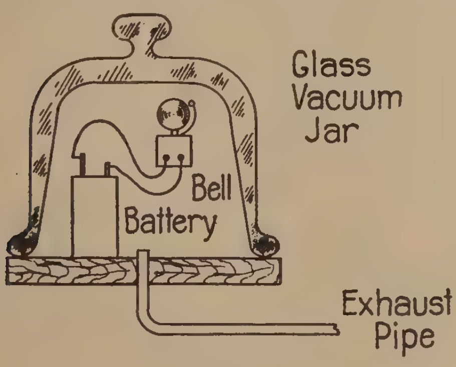



*Figure 103*

of travel. This rate of travel (or the velocity of the sound wave) is approximately 1,075 feet per second but varies to some extent with altitude and atmospheric conditions. The velocity of sound is very slow as compared with the velocity of light, heat or wireless waves, which are also a form of wave motion. We thus see a flash of lightning before we hear a clap of thunder or see the smoke dispelled from the muzzle of a gun before we hear the gun's report.

Unlike light, heat or electrical wave transmission, sound is an atmospheric disturbance. A vibrating bell, placed under an inverted glass bowl over a brass plate having an outlet through its center to which an exhaust pump is connected, may be heard almost as distinctly as though there were no glass container; but, if the air is exhausted until there is a vacuum about the bell, no sound can be heard, yet the bell may be seen vibrating as clearly as before the glass container was exhausted (Figure 103). We thus learn that there must be an atmospheric medium for the transmission of sound.

If the sound's source is a vibrating mechanism in simple form, such as a simple to-and-fro motion of the prong of a tuning fork, and is sustained without decay for a definite interval of time, the wave motion is said to be "simple harmonic". (A simple harmonic wave may be represented by the sine curve already discussed in Article 44.) On the other hand, if the source consists of a complex mechanical motion or an object vibrating by parts as well as in its entirety, the wave is **complex,** or a sine wave containing **harmonics** which give it **quality.** A sine wave without harmonics is called a pure wave. A complex wave is called an **impure** wave.

The sound sensation produced by a series of successive waves identical in form is called a "tone", and if each wave is **complex,** it is a **tone having timbre or quality,** but if **simple** or a sine wave, it is a **pure tone.** Sound that is produced by a series of successive waves not identical in form is called a **noise.**

A vibrating mechanism giving a pure tone is said to establish a tone of low pitch if it is vibrating slowly, but if vibrating rapidly, it establishes a tone of high pitch. The lowest pitch which is audible to the trained ear lies somewhere in the octave between 16 and 32 vibrations per second. The ear will not respond to a slower vibration. On the other hand, the trained ear has an upper limit of audibility lying somewhere in the octave between 16,000 and 32,000 vibrations per second. These two octaves are the extreme limits of the scale of audibility.

**Audible sound is thus defined as a disturbance in the atmosphere whereby a form of wave motion is propagated from some source at a velocity of 1,075 feet per second, the transmission being accomplished by alternate condensations and rarefactions of the atmosphere in cycles having a fundamental frequency ranging somewhere between 16 per second and 32,000 per second.**

The superposed waves on the fundamental, which we have called harmonics, are present in most distinctive sounds and particularly in the human voice.

They permit us to distinguish notes of different musical instruments when sounded at the same pitch. They also establish subtle differences in the voice which may indicate anger or joy or permit us to distinguish the voice of one person from that of another. Figure 104 illustrates wave forms for different kinds of sound and, similarly, Figure 105 shows the predominating wave shape of certain spoken vowels.

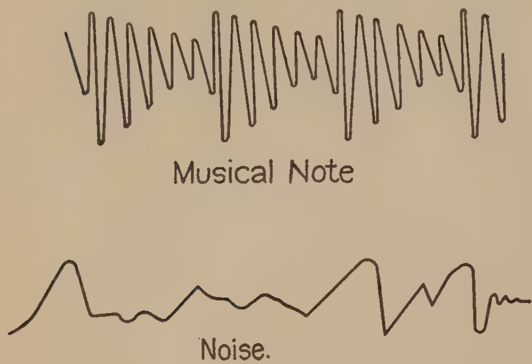



*Figure 104*

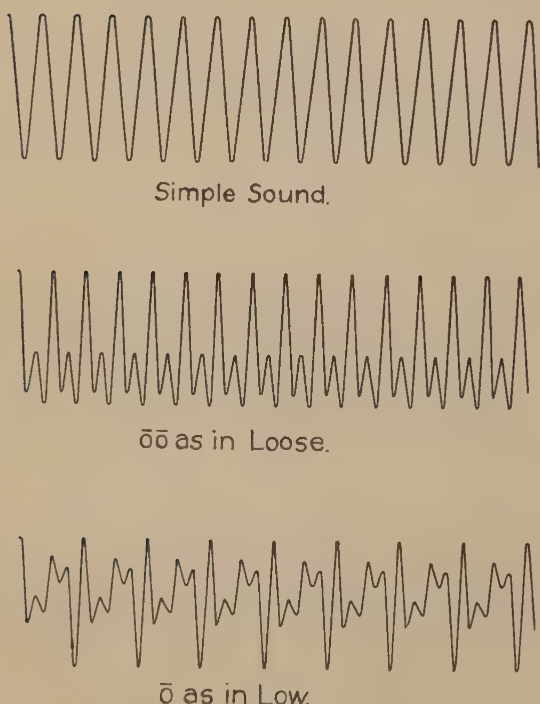



*Figure 105*

Fortunately, in telephone transmission, which is essentially a problem of conveying "intelligibility" from the speaker to the listener, we are not seriously concerned with sounds having either fundamental or harmonic frequencies that extend throughout the entire scale of audibility. The sound frequencies which play an important part in rendering the spoken words of ordinary conversation intelligible are the band of frequencies within the audible scale ranging from approximately 200 to 3,000 cycles per second. Within this band the frequencies between 700 and 1,100 cycles per second are perhaps of greatest importance.

### 60. The Simple Telephone Circuit

The original telephone, as invented by Bell in 1876, consisted of a ruggedly constructed telephone receiver. It was used both as a transmitter and a receiver at that time. The telephone circuit in its simplest form consisted of two wires terminated at each end by such an instrument but without transmitter or battery and without signalling features. Figure 106 shows such a circuit.

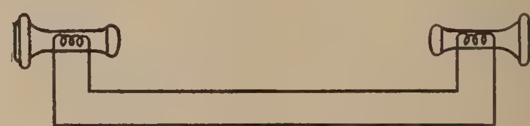


*Figure 106*

At the speaker's station, the sound waves of the voice strike the metal diaphragm of the telephone receiver, and the alternate condensations and rarefactions of the atmosphere on the side of the diaphragm establish in it a sympathetic vibration Behind the diaphragm is a permanent bar magnet and the lines of force leaving the magnet are crowded in the vicinity of the metal diaphragm. The vibration of this diaphragm causes a corresponding change in the number of lines of force that thread through the receiver winding resulting in the turns

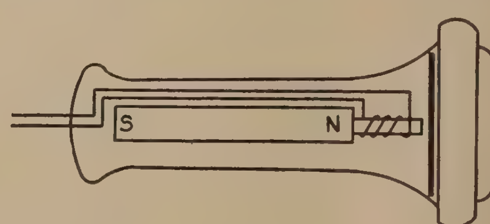



*Figure 107*

of the winding being cut by the building up and decaying lines. This establishes a varying electrical current in the winding of the telephone receiver having wave characteristics similar to the characteristics of the sound wave. This current in passing through the receiver winding at the distant end, alternately strengthens and weakens the magnetic field of the permanent magnet, thereby

lessening and increasing the pull upon the receiving diaphragm which causes it to vibrate in unison with the diaphragm at the transmitting end, although with less amplitude. This vibrating diaphragm reproduces the original sound, conveying "intelligibility" to the listener at the receiving end.

The earlier forms of telephone receiver were equipped with a permanent bar magnet as shown by Figure 107. The instrument's efficiency was greatly increased by the use of a horseshoe magnet as illustrated by Figure 108, which permits the lines of force to pass from one magnetic pole to the other through the iron diaphragm. This, with the additional refinements in construction which have been developed from time to time, constitutes the present telephone receiver.

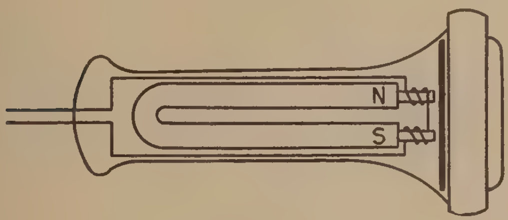



*Figure 108*

Although the principle of Bell's original telephone applies to the present day telephone receiver, it was appreciated in the early stages of telephone development that the electrical energy generated by a diaphragm vibrating in a comparatively weak magnetic field was insufficient for the transmission of speech over any considerable distance. The energy could, of course, be increased by using stronger magnets, louder sounds and the best possible diaphragms, but even with any ideal telephone receiver that might be perfected, voice transmission would

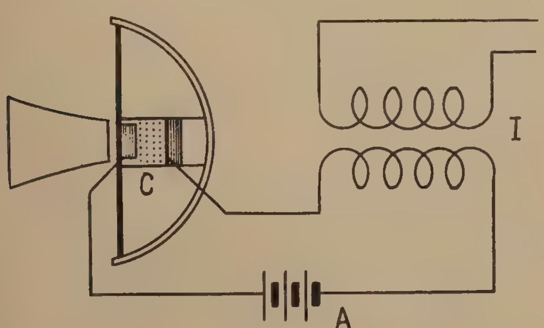



*Figure 109*

be limited to very short distances. One year after the invention of the original telephone, the Blake transmitter was introduced. It worked on the principle of a diaphragm varying the strength of an already established electrical current instead of generating electrical energy by means of electromagnetic induction. By this means it was possible to establish an electrical current with an energy value much greater than that conveyed to the instrument by a feeble sound wave, the battery in this case being the source of energy and the vibration of the diaphragm acting as a means for regulating this energy supply rather than as a generating device. The principle of the transmitter may be better understood by referring to Figure 109, in which battery A establishes a direct current in a local circuit consisting of the primary winding of an induction coil I, and a cup of carbon granules C. One side of this cup rests against a small carbon disk rigidly connected to the transmitter diaphragm. The vibrating transmitter diaphragm varies the pressure on the carbon granules which causes the resistance of the electrical circuit through the carbon granules to vary correspondingly, thereby causing fluctuations in the value of the direct current maintained in the circuit by the battery. These fluctuations, though represented by varying **direct current values** instead of by an alternating current, as in the case of the telephone circuit in Figure 106, will establish an alternating E.M.F. in the secondary winding of the induction coil which sets up an alternating current through the local receiver, over the line and through the distant receiver. The operation of the distant receiver, however, is no different than that explained in connection with Figure 106.

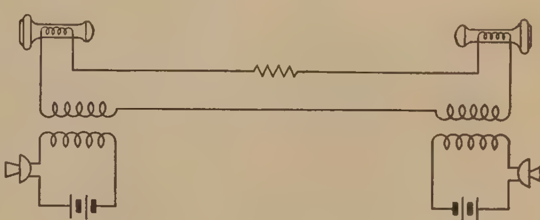


*Figure 110*

Figure 110 shows transmitters used at the ends of a simple telephone circuit. When the magnetic field is established by the fluctuating current through the primary of the induction coil **an alternating current** is induced in the secondary of the coil and this current flows through the receiver at the same end of the circuit, giving "side tone" to the receiver at the home station, and is also transmitted to the distant station, operating the receiver at that point.

A simple two-party magneto telephone circuit without central office connections and with the hook switch omitted for clearness, is shown in Figure 111. Signalling is accomplished by means of a magneto hand generator, which when turned at normal speed is automatically connected in the circuit by a spring mechanism associated with the crank and generates an alternating voltage of approximately 20 cycles frequency and ranging in value from 50 to 75 volts. The resultant alternating current operates a polarized telephone bell

at the distant end of the circuit similar in type to one which will be described in Chapter XIII.

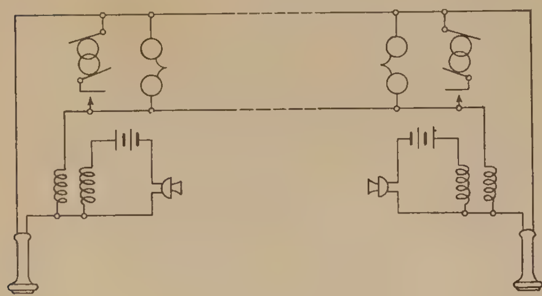


*Figure 111*

### 61. The Simple Magneto Exchange

Figure 112 is a schematic circuit drawing of two magneto telephone stations connected to a non-multiple magneto switchboard. In this figure, the hook switch has been added to the subscriber's station circuit. This permits opening the transmitter circuit and, incidentally, the line circuit when the telephone is not in use, which increases the life of the dry cells and eliminates the receiver from the line circuit, thereby leaving the line free for the transmission of ringing signals. At the central office, the subscriber's circuits terminate in jacks with bridging drops. There are several types of these drops but the one shown in the figure will illustrate the operation of a commonly used self restoring type. Referring to the drop designated as $D^1$, the ringing current of the calling party's generator gives a pulsating magnetization of magnet M. This attracts the armature $A^1$ and trips the armature $A^2$ which in dropping forward lifts the shutter S, displaying before the operator a number on the armature $A^2$.

The operator answers this incoming call by inserting the plug $P^1$ of her cord circuit into the jack $J^1$. This disconnects the bridged (connected across) drop winding, preventing it from shunting the talking current transmission, and energizes a second winding W of the drop, which operates the armature $A^2$ and restores the signal automatically without a second manual operation on the part of the telephone operator. A key L permits the operator to answer the calling party by connecting her head set to the particular cord circuit she has used. She then inserts the plug $P^2$ of the other end of her cord circuit into the jack corresponding to the number of the called line and operates a second key R which disconnects this end of her cord circuit from her head telephone and the calling party

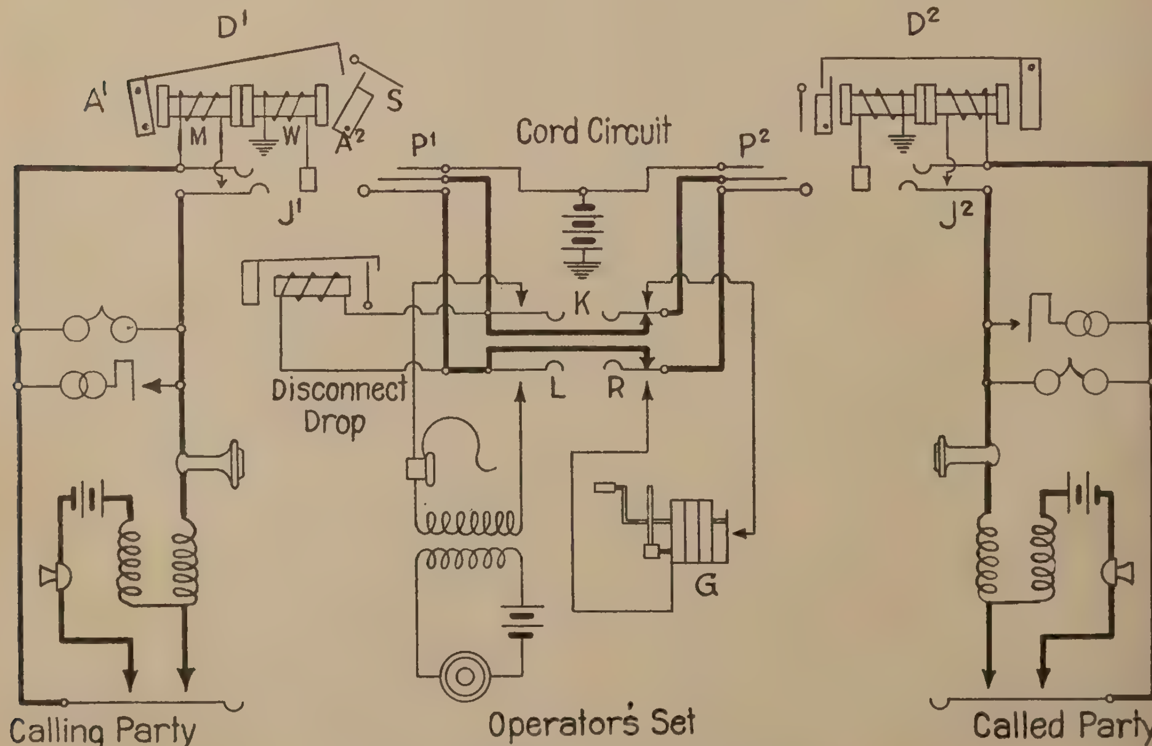



*Fig. 112—Magneto Exchange Connection*

and connects it to the generator G. She is now able to ring the called party by turning the generator crank. In the larger magneto offices which are equipped with ringing machines the operation of key R connects the cord circuit with ringing leads that are energized at all times and the necessity of turning a ringing generator associated with the switchboard position is eliminated.

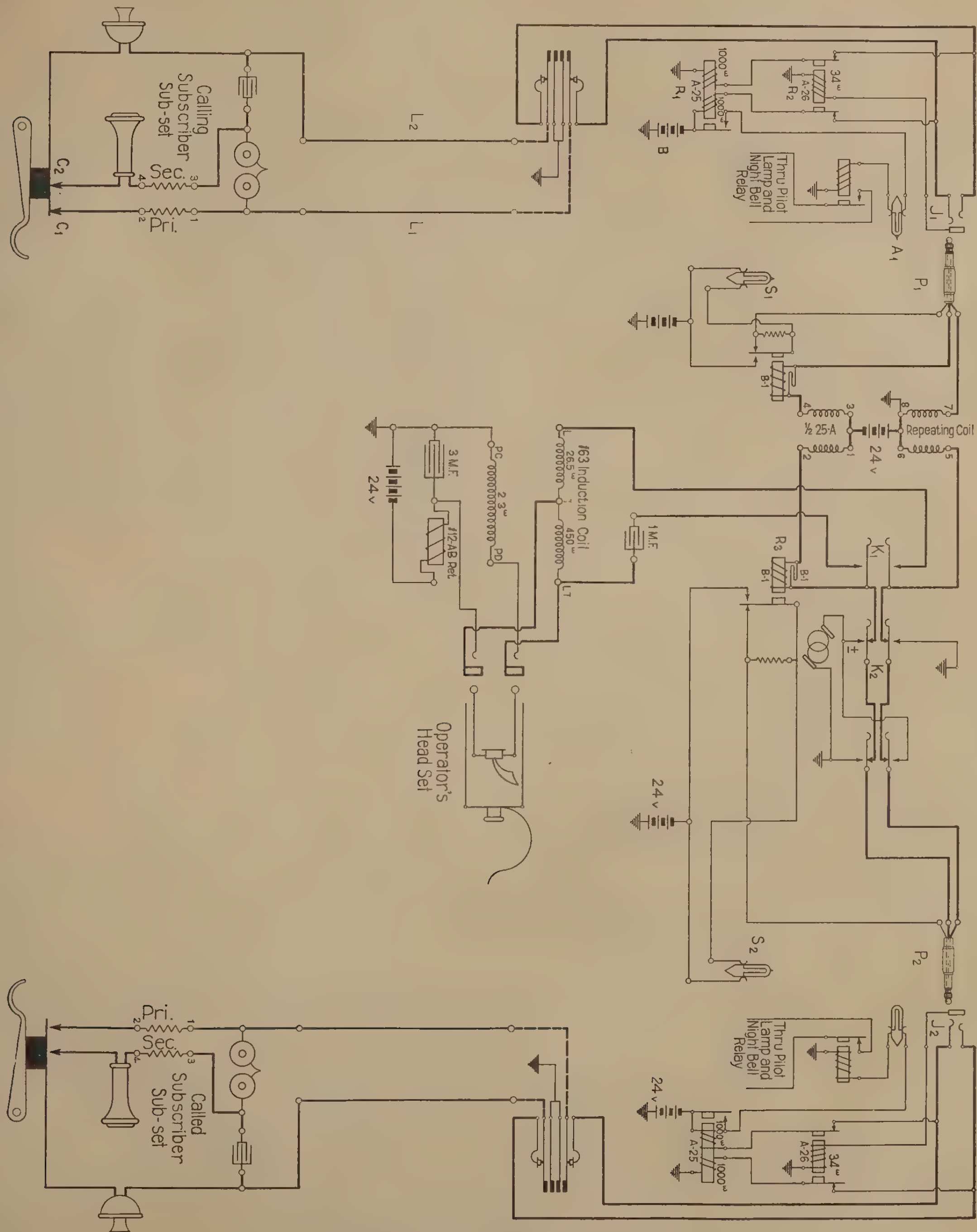



*Fig. 113—Common Battery Connection.*

## 62. The Common Battery Telephone Exchange

In Chapter VIII we learned that it is possible for a number of circuits to be energized from a single battery, and that if the battery has a very low internal resistance the operation of any one of these circuits does not interfere with the operation of any other. Figure 113 shows a telephone connection between two common battery stations terminating at the same central office. Here the telephone circuit at each station is normally open when the receiver is on the hook, with the exception of the ringer winding which is bridged across the circuit in series with a condenser. It is a function of the condenser to close the circuit for alternating current and open it for direct current. Accordingly, the line is open in so far as the subscriber's signalling the operator is concerned and is closed through the ringer in so far as the operator's ringing the subscriber is concerned; or we may say, the circuit is in such condition that the subscriber may call the operator or the operator may call the subscriber at will. The subscriber calls the operator by merely closing the line which is accomplished by removing the receiver from the hook. Contacts $C_1$ and $C_2$ are made at the hook switch. $C_1$ closes the line through the transmitter in series with the primary of the induction coil. This permits current to flow from the central office battery B through one-half of the line relay winding $R_1$, over one side of the line $L_1$, through the primary winding of the induction coil and the transmitter back to the central office over the other half of the line $L_2$, through the other half of the relay winding $R_1$ to the other side of the central office battery or to ground, i.e., the grounded side of the battery. This energizes the line relay $R_1$ and connects the central office battery to a small answering lamp $A_1$ in the face of the switchboard in front of the operator. This lamp lighting, indicates to the operator that this particular line is calling. She answers the call by inserting plug $P_1$ into the jack associated with the lighted lamp and to which the line of the calling party is connected. A third battery connection to the sleeve of her plug $P_1$ closes a circuit through the winding of a second relay $R_2$, known as a "cut-off" relay, which disconnects the line relay from the circuit, putting out the burning answering (or line) lamp $A_1$. She answers the call by connecting her telephone set to the cord circuit by means of the listening key $K_1$. She talks over the two heavy conductors of the cord circuit through the windings of the repeating coil, which, by means of transformer action, induces current into the other windings of the same coil; this flows back over the calling subscriber's line and induces a current into the secondary of the induction coil which flows through the condenser and the telephone receiver.

Not only does the operator's voice current flow from the central office cord circuit to the subscriber's receiver, but there is a direct current furnished by the central office battery through two of the four windings of the repeating coil of the cord circuit over the line and through the subscriber's transmitter. This corresponds to the transmitter current furnished by a local battery in the magneto set and permits the subscriber to talk by virtue of the transmitter carbon resistance varying the strength of this current, which, by means of the repeating coil windings at the central office, induces an alternating voice current across to the opposite side of the cord circuit.

Upon ascertaining the number of the party called, the operator inserts plug $P_2$ into jack $J_2$ which permits the lamp $S_2$ to burn on account of its circuit being closed from the central office battery through the sleeve of the plug $P_2$ and the sleeve of the jack $J_2$. This lamp tells her that the receiver is on the hook at the called party's station and that she must give this connection attention by ringing the called party at frequent intervals. This is accomplished in the same way as in the magneto exchange, by operating the ringing key $K_2$. When the called party answers, current, flowing from the central office battery through the windings of the repeating coil, and through the supervisory relay $R_3$, will operate this relay. When this happens the lamp is short-circuited and goes out, notifying the operator that the party has answered. At the same time a resistance is inserted in the battery circuit to limit the current flow. When both parties have finished talking and hang up their receivers, this supervisory relay, as well as a similar relay on the other side of the cord circuit, is de-energized, and since the short-circuit is then removed from the lamps, they light. This notifies the operator that both parties are through talking and that both cords are to be taken down. When the operator pulls down both cords, the sleeve circuit of the cord is opened at the jack and the lamps go out.

It is seen that the operator depends upon burning lamps for each operation, excepting that of answering and ascertaining the number from the calling subscriber and that of connecting the calling cord to the jack of the called station. In all common battery operating, **a burning lamp means attention.** Thus a burning lamp in the face of a

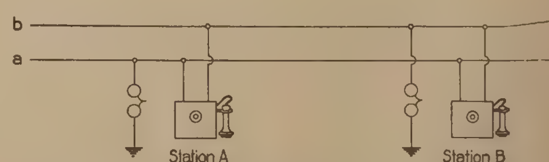
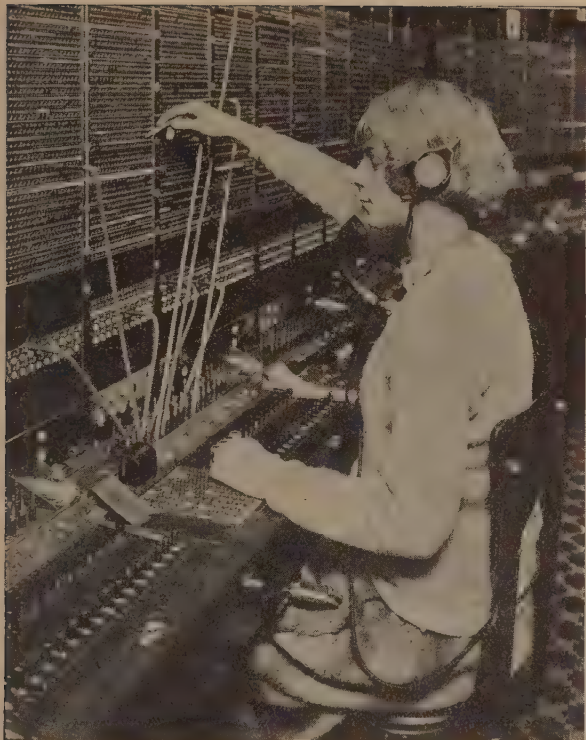



*Fig. 114—Ringer Connection for two Party Line.*

switchboard signifies "line to be answered"; one burning lamp on a cord signifies "continue ringing on the corresponding cord"; two burning lamps signify "disconnect both cords as both parties have 'hung up'". A flashing lamp means one party is not hanging up but wishes to place another call or desires the operator to answer in on the connection.



# LOCAL OPERATING

*Above*—"A" Switchboard in large common battery exchange of multi-office district.

*Above*—Close-up of "A" switchboard position showing trunk multiple, answering jacks and operator's key shelf.

*Right*—Close-up of "B" switchboard position.

*Below*—General view of "B" switchboard in large exchange.

## 63. Party Lines and Selective Ringing

In common battery operation in order to put more than one subscriber on the same line, it is necessary that some means be provided for signalling each party at will. One method of doing this is represented by Figure 114, where the same two-wire circuit is used for two subscribers, but one subscriber is rung over wire **a** to ground and the other over wire **b** to ground. A more complex system makes use of the "biased" ringer, which is shown in Figure 115. In this ringer, the magnetic circuit through the cores of the two windings is completed through a permanent steel magnet which gives what is known as a "polarized magnetic circuit". To give the bias effect a small spring is provided to keep the soft iron armature normally in one position. Without tension on the biasing spring, a current flowing through the windings in one direction will increase the pull on one end of the armature and decrease the pull on the other. This permits the tapper to strike one gong. Likewise, if the current flows in the opposite direction, it will permit the tapper to strike the other gong. An alternating current will, therefore, ring the bell. But, if two such ringers are placed in the same circuit and they are biased in opposite directions, obviously a pulsating direct current in one direction will ring the first ringer, while in the other direction it will ring the second.

These two systems may be combined by placing two biased ringers between each wire and ground, thus making a four-party system.

Another system that is used to some extent is known as the "harmonic system". Each ringer is constructed with a special spring armature having a weighted tapper to give it a natural period of vibration. The period of vibration is different for each ringer on a single line and the alternating ringing current must have a corresponding frequency to select a particular ringer. This system requires ringing current taps at the operator's cord circuit of various frequencies instead of the several arrangements of a single frequency required for the first system described.

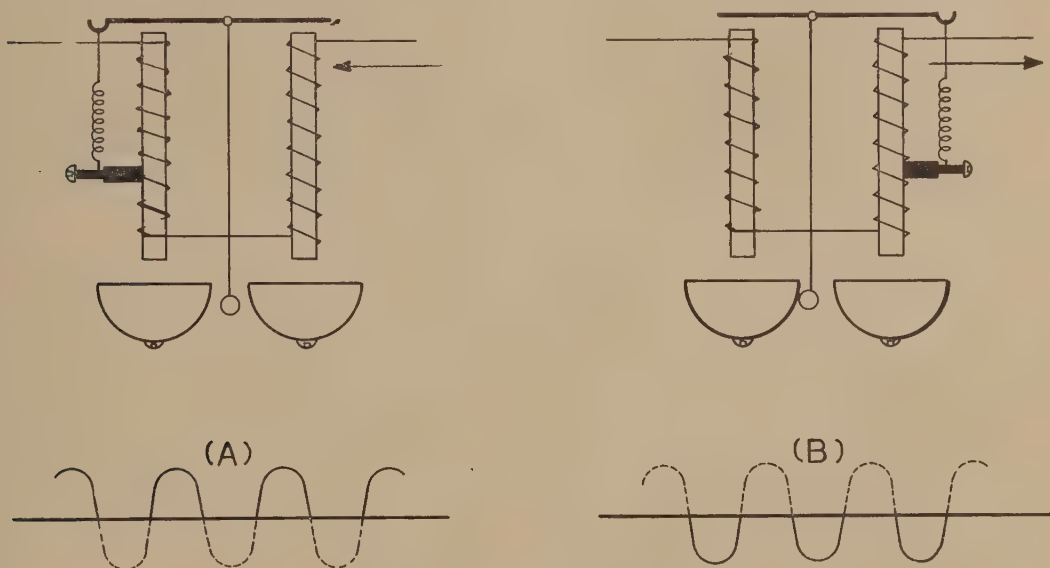



*Fig. 115—Theory of "Biased" Ringer*

## 64. The Multiple Switchboard

In a small exchange where a single operator can handle all of the subscribers, it is possible to connect any two subscribers together with each subscriber's line terminating in a single jack only. As described in the foregoing, if subscriber "A" signals the operator, she will plug into his answering jack, which is next to the signal by which he calls her, and upon ascertaining the number he is calling, for example subscriber "B", she will connect him by plugging into the answering jack of subscriber "B" with the other plug of the same cord circuit. However, when there are more than a few hundred subscribers, all of whose lines terminate at the same switchboard, it is obviously impossible for one operator to answer all of these lines, as it is also impossible to put a larger number of answering jacks and signals within reach of a single operator. To apportion the work and to make it possible to mount the switchboard apparatus in such a way that it will permit interconnection for a large number of lines, the **multiple switchboard** was developed.

The principle of the multiple switchboard is that the answering jacks and signals are divided up among the various operators, each operator handling on the average about two hundred lines and being responsible for answering any signals from these subscribers. In addition to these answering jacks there may be 3,300 **calling jacks** in the position in front of each operator. These calling jacks do not have any signals mounted with them as they are for calling only. The calling jacks are each multipled, that is, connected in parallel with a similarly located jack in the third position to the left and right and with the answering jack. Any operator can reach any one of about 10,000 calling jacks, either directly in front of her or in the adjacent positions on her left or right. A multiple switchboard is shown diagramatically in Figure 116. In this figure should subscriber Number 109 call subscriber Number 567, the signal would come in at position "1" where the answering jack for subscriber 109 is located and the operator would connect him by plugging into calling jack Number 567 in the multiple to her right (Position 2). On the other hand, if subscriber 567 called subscriber 109, the operator at position 3 would answer his call and connect him to subscriber 1 by means of the calling jack in the multiple to her right (Position 4). Each operator is warned against plugging into a busy line by means of a "click" which is heard in her head receiver when she starts to plug into a calling jack already in use somewhere else in the multiple.

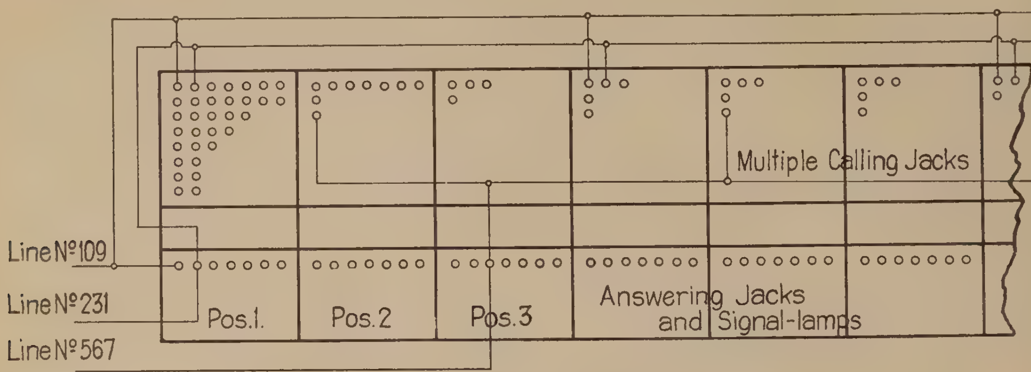



*Fig. 116—Principle of Multiple Switchboard.*

**Note**:—A trunked connection between subscribers whose lines terminate at different central offices does not involve apparatus features distinctly different from those of the toll switching trunk to be described in Chapter XIII so that it is not covered in this Chapter.

# CHAPTER XI

## PRINCIPLE OF THE TELEGRAPH

### 65. Means of Obtaining Telegraph Circuits

In the Bell System the telegraph service may be properly considered as being incidental to the furnishing of telephone service. In other words, it is, in a sense, a "by-product" of the telephone service. Nearly all of the telegraph circuits are obtained from wire facilities created and used primarily for telephone service which means that in all cases special methods and apparatus must be employed in order to make possible the use of the same circuit facilities for telephone and telegraph service. This is accomplished by four different methods as follows:

1. Either simplexing or compositing open wire circuits and equipping the wires so derived with single line or duplex repeater sets, thereby securing an open wire direct current telegraph system.
2. Further superposing on the open wire circuits high frequency alternating current channels commonly called "carrier telegraph circuits".
3. Superposing on the telephone circuit of a cable pair (two wires) a very low current telegraph system which uses a special type of repeater equipment known as the D.C. Metallic Repeater.
4. Using cable pairs for telegraph carrier circuits employing much lower frequencies than the open wire carrier system, but which, though superposed on the D.C. metallic system cannot be superposed on a telephone circuit.

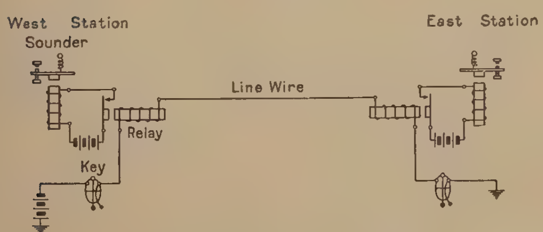



*Fig. 117—Simplest Telegraph Circuit.*

While it is neither desirable nor possible in this and the succeeding Chapter to describe all of the above telegraph systems fully, we shall take up those electrical principles that are fundamental to each and more or less common to all. In general, these are applications of theory already discussed, and after a brief review of the circuit theory of the various apparatus units and the layouts met with in practice, we shall study in particular the relation of relay adjustments to proper current flow.

### 66. The Telegraph Circuit in Its Simplest Form

The telegraph circuit in its simplest form consists of a wire between two points, equipped at each end with a telegraph set. These are so arranged that one set is connected to ground and the other connected to grounded battery, or both sets are connected to grounded batteries of opposite polarities.

Figure 117 illustrates such a "neutral" telegraph circuit. Let us assume that the west station key is closed and the east station key is open ready for sending. If now the east operator closes his key for only an instant, the signal is sent through both the east and west relay windings in series, and these relays operate the local sounder circuits, giving a quick, complete stroke of the sounder lever corresponding to a "dot". If the key lever is held closed for a little more than 1/10th of a second, another signal is transmitted giving a slower stroke of the sounder lever corresponding to a "dash".* If the west station desires to stop the east station from sending, he "breaks", i.e., he opens his key, thereby opening the circuit, and the operator at the east end, noting the failure of his own relay to respond to signals, knows that the west end is trying to break. He then closes his key (with the "locking" lever) which short-circuits the contacts of the sending or "non-locking" lever. The west station can now send to the east station. A telegraph circuit such as that shown by Figure 117 cannot be made up of a line wire forming a part of a telephone circuit. To derive a telegraph wire the telephone circuit must be equipped with either a simplex set, which permits one telegraph circuit over a physical telephone circuit of two wires (not phantomed) as shown by Figure 118, or with a composite set which provides one telegraph circuit over each wire of a telephone circuit, as shown by Figure 119.

The simplex telegraph circuit cannot interfere with the telephone conversation because the telegraph currents will divide equally at the mid point of the "simplex" or "repeating" coil to which each telegraph set is connected. Any change in the current value at the "make" or "break" cannot be induced into the telephone circuit because the magnetic field established by half the telegraph current

*For the benefit of those readers who are not familiar with the American Morse Code, the alphabet and numerals are as follows:
A .– B –... C .. . D –.. E . F .–. G ––.
H .... I .. J –.–. K –.– L — M –– N –.
O . . P ..... Q ..–. R . .. S ... T – U ..–
V ...– W .–– X .–.. Y .. .. Z ... . & . ...
1 .––. 2 ..–.. 3 ...–. 4 ....– 5 –––
6 ...... 7 ––.. 8 –.... 9 – – 0 —

flowing in one-half of the repeating coil is exactly neutralized by the other half of the telegraph current flowing in the other half of the same repeating coil. Referring to Figure 118, the arrows represent the telegraph currents, and the total current is shown dividing at the mid point of the simplex coil line winding at station A. The two halves join again at the mid point of the coil at station B. It is imperative that the two line conductors have the simplex coil windings, and the larger part will induce a current in the "drop winding" of the coil that cannot be neutralized by the current induced by the lesser part.

The composited telegraph circuit cannot interfere with the telephone conversation because the series inductance of the 5-AA retardation coil together with the 6 microfarads capacity connected

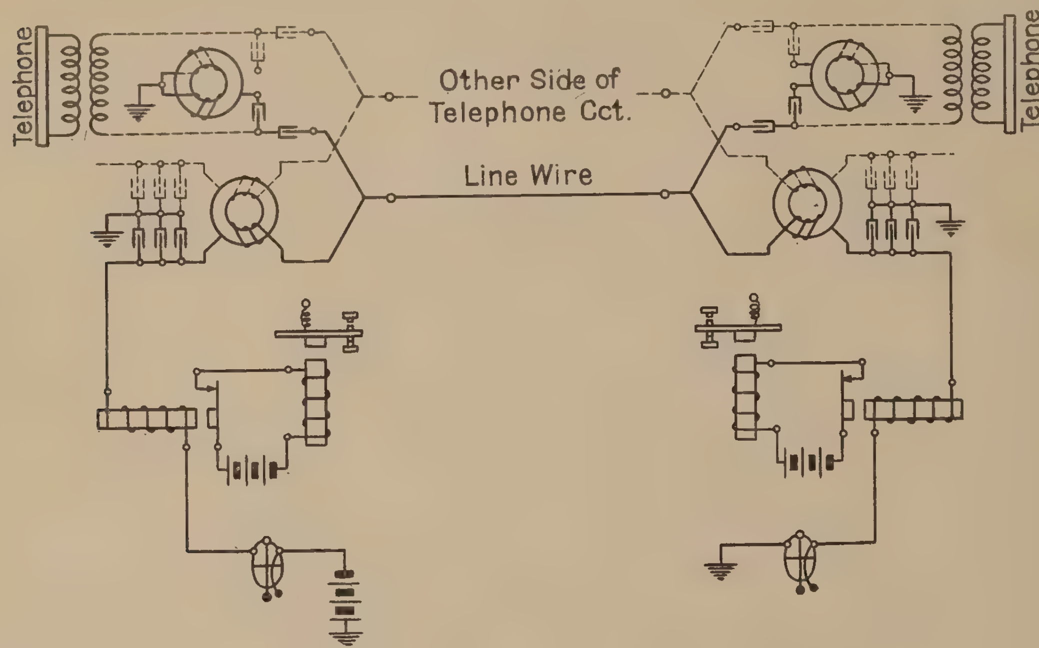



*Fig. 119—Telegraph Circuit on Composited Telephone Circuit.*

identical electrical characteristics, including not only equal or "balanced" series resistances, but equal or "balanced" capacities and leakages to other conductors and to ground. If the two line conductors are not so balanced, the telegraph current will not split into equal parts at the mid point of

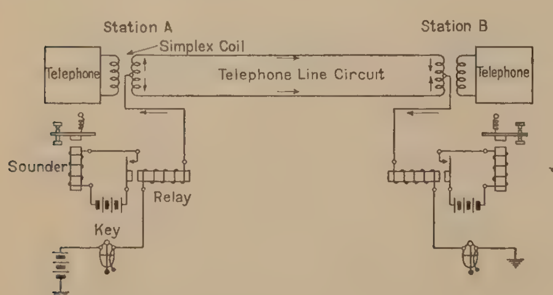



*Fig. 118—Telegraph Circuit on Simplexed Telephone Circuit.*

to ground prevents sudden changes in current values which otherwise would be distinctly audible in the telephone receiver. The inductance here serves as a "choke coil", that is, it opposes the building-up of the current at the "make" of the key and retards the decay of the current at the "break"

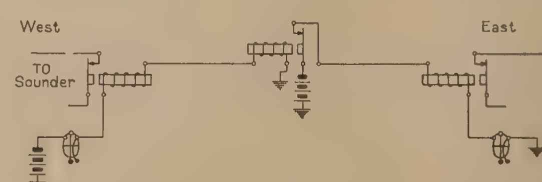



*Fig. 120—One-way Telegraph Circuit with Relay Used for Repeating Signal.*

of the key, in this way preventing extremely rapid current changes which might induce E.M.F.'s of sufficient magnitude to affect telephone service, The condensers assist the inductance by storing up

a quantity of electricity while the key is closed, and discharging this electricity through the inductance coil when the key is open. The net result is to produce a current which has less abrupt changes and the voltages induced at the break are lowered, thereby preventing a voltage greater than the operating voltage being impressed at any instant. The condenser in series with the telephone drop prevents the telegraph current from reaching the telephone, and the bridge, consisting of two 2-microfarad condensers in series with the windings of a second 5-AA retardation coil connected to ground at the mid point, forms a "crossfire" bridge which stabilizes the potential of all wires used for telegraph circuits and minimizes the trouble caused by false operation of telephone signal relays. "Crossfire" is a condition where the signals on one telegraph wire induce voltages sufficient to disturb signals sent on another wire, or sufficient to operate the signal relays on the same or adjacent telephone circuits.

### 67. The Neutral Telegraph Repeater

The telegraph circuits in their simplest form, explained in the foregoing Article, are such as two testboard men might establish in emergencies by using the telegraph sets installed on the keyshelves of their respective testboard positions for establishing quick telegraphic communication between each other. Such layouts are seldom used, however, for telegraph service, and when so used must be restricted to comparatively short distances. With such an arrangement, the amount of energy that could be sent over a very long circuit would not be sufficient to produce satisfactory telegraph signals. It is, therefore, necessary to break the long circuit up into "links" of shorter circuits, with each "link" relaying the signals into the next adjacent one. Figure 120 represents a telegraph circuit similar to that shown in Figure 117, but with an intermediate relay at a mid point in the circuit. This will permit the west station to send to the east station over a much longer wire because the signal is reenergized at the intermediate station by a new battery connected to the contacts of the intermediate relay. It can be easily seen, however, that the east station cannot send to or "break" the west station. The circuit will work in one direction only. With such a layout two circuits would be required between the two stations to permit communication in both directions. These are represented by Figure 121, and the first telegraph connections required a duplicate circuit of this kind to permit communication in both directions. From an economic viewpoint, however, this scheme of telegraphing over greater distances would require twice the number of wire facilities, and would be unsatisfactory for this reason. From a telegraph subscriber's viewpoint, the class of service which would be given would be entirely different from that given by Figure 117 and might or might not be preferable to it. With this new arrangement it would be possible for one subscriber to send a message in one direction while the other subscriber was sending a message in the opposite direction,

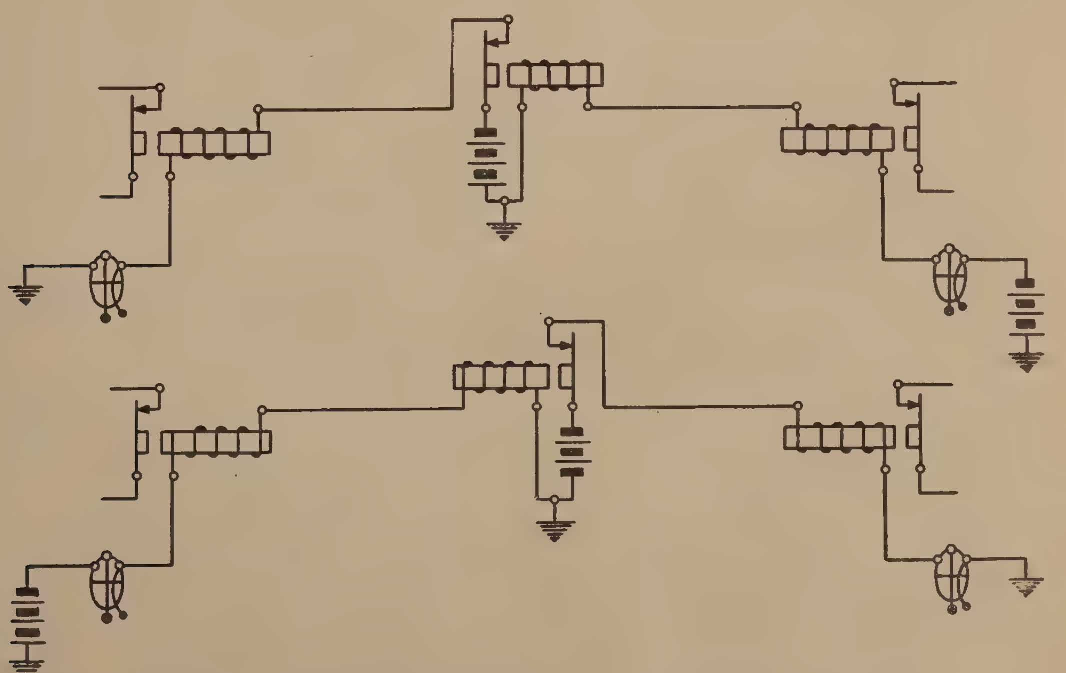


*Fig. 121—Two One-way Telegraph Circuits to Permit Transmission in Both Directions.*

and in this respect the transmitting capacity of the service would be doubled. On the other hand, neither station could break the other without actually interrupting the transmission over the other wire and sending a "break" message. Although today considerable use is made of a so-called "full duplex" service to be described later, the above arrangement is more or less awkward for the ordinary telegraph service. The first solution to this problem, or the problem of giving service over one telegraph wire which would permit one operator to "break" the other, was the use of the neutral telegraph repeater (3-A telegraph repeater).

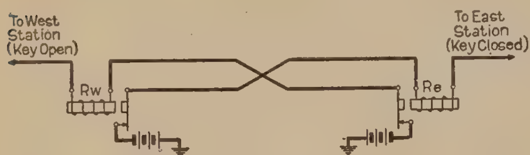



*Fig. 122—Simplified Telegraph Repeater without Holding Coils.*

The theory of this repeater can be best understood by studying each feature step by step. As previously brought out, it is expected primarily to relay energy in the same way that the relays in Figure 121 relay energy, but its operation is restricted to a single wire and it must permit one operator to break the other. First, let us suppose that the two intermediate relays are connected to

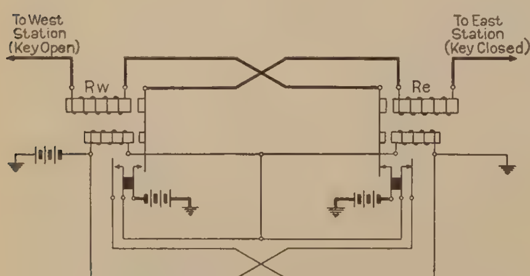



*Fig. 123—Simplified Telegraph Repeater Circuit.*

a one wire circuit, as shown by Figure 122, with the winding of one relay connected in series with the contacts of the other and vice versa. Such an arrangement will not work for the following reasons. Let us assume that the west operator starts to send a message to the east operator. He opens his key, which at the intermediate point lets the armature of the relay designated as $R_w$ fall back and open the circuit east. This will result in the armature of the relay designated as $R_e$ falling back and again opening the circuit west, which is already open at the key. If now the west operator closes his key, the relay $R_w$ will not respond as the circuit is open at the contacts of the relay $R_e$. Consequently, both circuits are open and the closing of either or both keys cannot restore the contacts of the $R_e$ and $R_w$ relays. **It is, therefore, necessary to provide an additional coil to each relay, so wired that it will hold the armature while the other circuit is open regardless of whether or not the corresponding circuit is open.** These coils are called "holding coils", and Figure 123 represents the same connection as shown in Figure 122 but with the additional holding coil feature. The battery circuit for the holding coils is a local one, and is not connected to the line wires in any way. It is represented by light lines to distinguish it more clearly from the main line telegraph wires. The two holding coils are in series, and each line relay is equipped with an additional set of contacts which shunt the holding coil of the other relay when closed. The operation of the repeater is as follows: As before, let us assume that the key at the west end of the line is open and that the main line contacts of the corresponding relay $R_w$ of the repeater are open. The key at the distant end of the east line is assumed to be closed,

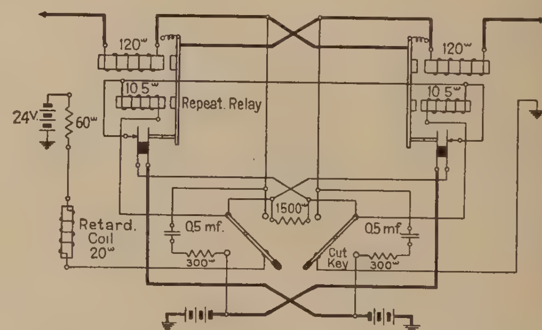



*Fig. 124—Circuit Diagram, No. 3-A Telegraph Repeater.*

i.e., we are assuming for the time being that a signal is being transmitted from west to east. This can now be accomplished since the holding coil of the $R_e$ relay is not shunted and will not permit its armature to fall back and open the west line when the signal is repeated from the west line into the east line by means of the $R_w$ relay's armature. If, however, the east operator desires to break while the west operator is sending and opens his key, the $R_e$ relay armature will fall back as the west operator continues to make a signal which closes his circuit and shunts the holding coil of the $R_e$ relay, thereby rendering this holding coil inoperative and permitting the $R_e$ armature to fall back. If now the east operator should send to the west operator, and later the west operator desires to break the east operator, this can be accomplished in the reverse order.

The actual wiring diagram of the standard 3-A telegraph repeater set is shown by Figure 124. Here a few other features of the circuit are shown which were omitted in Figure 123 for clearness.

To prevent sparking of the relay contacts in the main line, each set of contacts is bridged with a 300 ohm resistance in series with a 0.5 mf. condenser. Switches are provided on the set for "cutting" the circuit, i.e., separating the line east from the line west and using the two halves of the repeater set as terminating telegraph instruments without any interconnection between the two circuits. These switches also open the local battery circuit

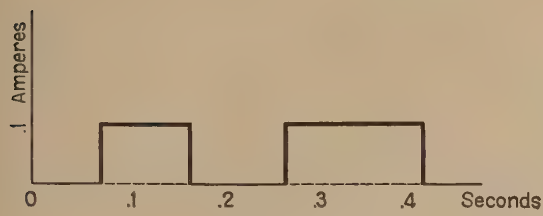



*Figure 125*

of the holding coils. A 1500 ohm resistance bridges the shunting contacts of the holding coils to prevent excessive sparking.. A small retardation coil is in series with the battery connection to the holding coils, and quickens the action of each holding coil when the shunt is removed by means of the inductive effect coming from the decrease in the current value of the local holding coil circuit.

### 68. Nature of Currents in Neutral Telegraph Systems

In any telegraph circuit such as those discussed in the foregoing, if we could ignore the time required for the direct current to establish itself and the time required for it to decay, we would have a perfect representation of the telegraph signal (for the letter "A") as illustrated in Figure 125. But every telegraph circuit must have some series inductance. Each line relay adds from one to two henrys, and in the case of the composited circuit each 5-AA retardation coil adds 2.7 henrys. The signal with series inductance, therefore, is more nearly that represented by Figure 126, each current pulse having a sloping curve from zero to maximum value at the "make" of the key and from maximum value to a

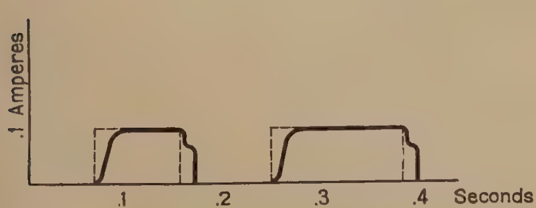



*Figure 126*

point where the arc is broken at the "break" of the key. If in addition to the inductance we consider the grounded condensers of the composite set, we have a further sloping of the pulse as shown by Figure 127. Here the shaded portion represents the effect of the condenser over and above the effect of the inductance. When the key is closed, the first rush of current flows only in part to the line since the inductance of the 5-AA retardation coil

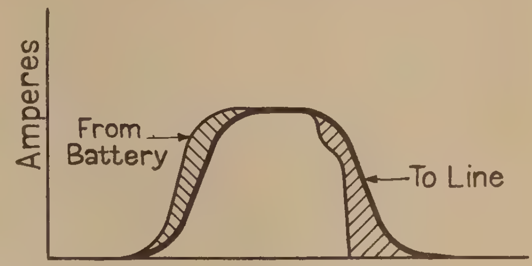



*Figure 127*

opposes its sudden "change in value" and it flows into the condensers charging this capacity to about the potential of the battery. When the key is opened the current does not stop flowing at the breaking of the arc because the discharging condensers sustain it for an instant.

In considering the relay adjustments necessary to give proper signalling, the shape of the current curve must be taken into account. Any relay, telephone or telegraph, has a definite operating current value and a definite release current value for any given adjustment. To illustrate this, let us refer to

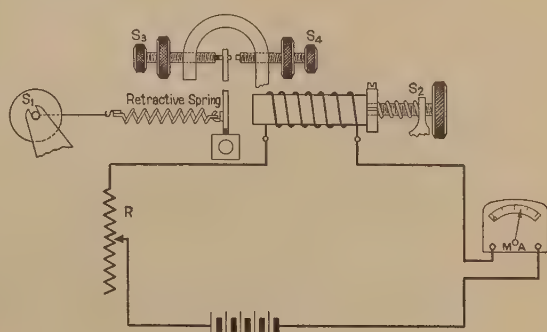



*Figure 128*

Figure 128 which shows a telegraph relay in series with a rheostat, a battery and a miliammeter. If the rheostat is adjusted so that the resistance in the circuit is too great to permit the battery to operate the relay, and the resistance is then gradually cut out of the circuit, there will be a definite miliammeter reading at which the armature of the relay pulls up. This reading is called the "operating current value" of the relay for the particular adjustment. If after the relay is operated, the rheostat is adjusted in the other direction so as to

increase the resistance of the circuit, the relay armature will fall back at a definite miliammeter reading. This is called the "release current" for the relay at the particular adjustment. The release current is usually smaller in value than the operating current for two reasons; first, because the magnetic circuit is much stronger when the armature is closer to the pole pieces so that the magnetic pull which holds the armature is greater than the pull which advances the armature, and second, there is some residual magnetism in the iron core at the time the circuit is broken that did not exist at the time the circuit was made. We might represent, therefore, by the points P and Q in Figure 129-A the operating and release current values respectively for a relay such as that illustrated by Figure 128. With this particular adjustment, the length of the signal will be the time indicated by "T". If we should now make certain adjustments of the relay either by weakening the tension of the retractile spring with the screw $S_1$,

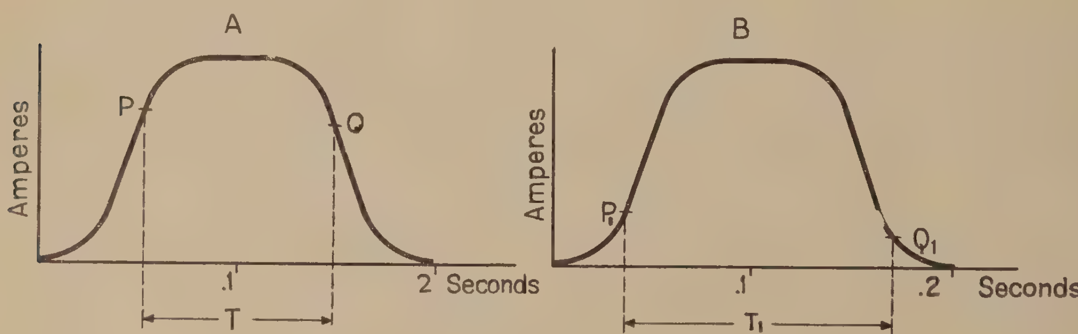



*Figure 129*

lessening the air gap between the pole pieces and the armature with the screw $S_2$, or decreasing the stroke of the armature by adjustments of the contact and back stop screws $S_3$ and $S_4$, we greatly decrease the operating and release current values, say to those represented by $P_1$ and $Q_1$ of Figure 129-B. The effect would be to increase the length of the signal from that represented by T to that represented by $T_1$. These adjustments would have changed the signal from "light" to "heavy". For the sake of contrast let us imagine that the wave shape of the signal was that shown by Figure 125. Here it is evident that we could neither increase nor decrease the length of the signal by relay adjustments.

To a degree this explains the frequent adjustments that are necessary on telegraph circuits in practice. If additional inductance is added to a circuit by inserting a relay winding in series, and for example, the adjustment happens to be that shown by Figure 130, the slope of the "make" and "break" of the signal is increased and a new adjustment may be required. The adjustment might be to lengthen the signal in one case and to shorten it in another. It would depend upon the original positions of points P and Q on the curve.

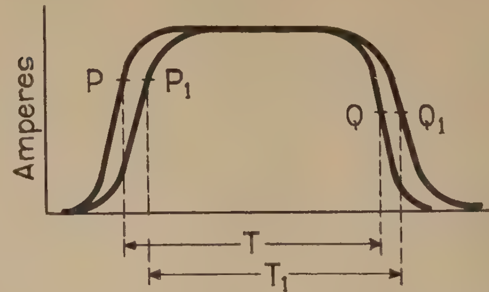



*Figure 130*

Another case is the decrease in current value resulting from a decrease in voltage value or an increase in series resistance which will change the length of the signal. Let us take the case of increasing the current by using higher voltage or taking series resistance out of the circuit. Here

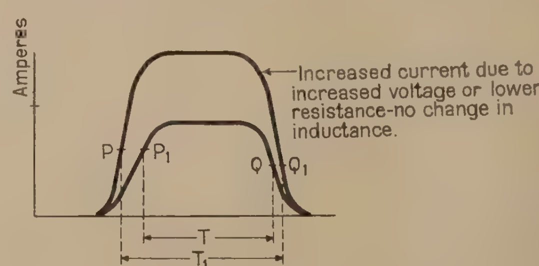



*Figure 131*

the operating and release current values of the relay before and after it is adjusted are the same, as illustrated by Figure 131, but are more nearly the maximum current values before the change is made than after, because the increase in current with constant inductance merely steepens the sides of the curve. The net result, however, is an increase in the length of "T", as illustrated in the figure.

In practice there is a third changing condition that affects adjustments, and this is the fluctuation in the current values due to leakage along the line. To a degree it can be compensated for by using grounded battery connections at both ends of the circuit, one end being positive and the other end being negative, instead of using a single battery at

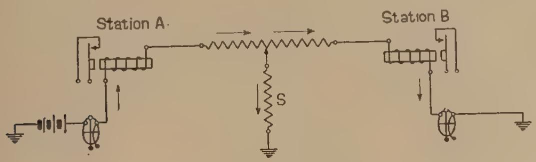



*Figure 132*

one end working to a ground at the other end. To understand this in principle let us assume the condition shown in Figure 132 where S represents a leak to ground along the line, either distributed or otherwise. First, let us suppose that Figure 133-A represents the current curve when there is no leak.

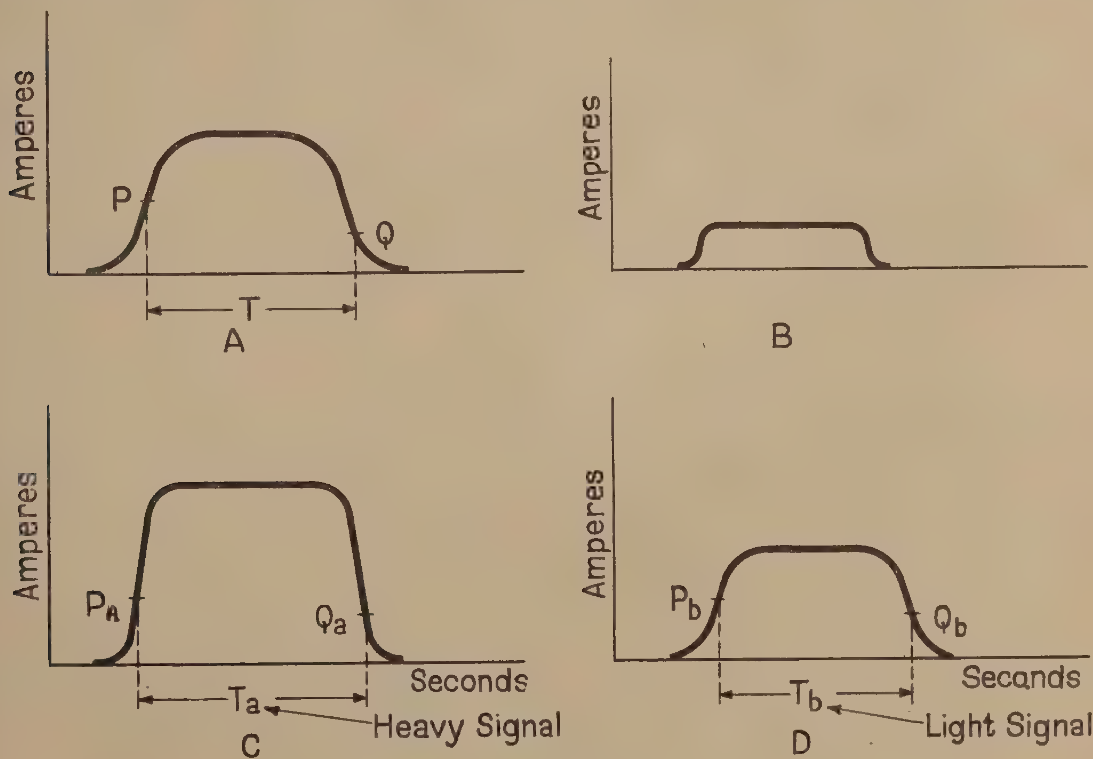



*Figure 133*

The leak will increase the current in the station A relay on account of the additional path through S, and since this path has less inductance we may represent the leakage current by the curve shown in Figure 133-B, which is perhaps much smaller in value but has steeper slope. Now, the curve B is going to influence the increased current through the A station relay by making it more nearly that represented by curve C, which is steeper, or will give a heavier signal. On the other hand, the leak S has a shunting effect on the current through the B station relay, and will not only tend to decrease the current but tend to flatten the curve as shown

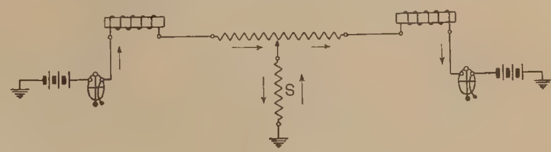



*Figure 134*

by Figure 133-D. This wide variation in the current flow through the two relays could not take place if the battery at station A had just half its voltage, and a second equal battery of opposite polarity was used at station B instead of direct connection to ground. The current flow will be more nearly constant through the relays at the two ends because we can assume that each battery is furnishing equal current to ground through the leak, and these currents, as illustrated by Figure 134,

tend to neutralize each other on account of flowing in opposite directions.

The shunt effect to ground for a leak, such as is shown by Figure 132, is a special case. On every telegraph wire, regardless of insulation conditions, we have in effect a "leak" to ground through the capacity between the wire and ground, or a condition that might be illustrated by substituting a condenser for the resistance S in Figure 132. Since the telegraph current wave forms are similar to alternating current cycles, we can imagine the condenser shunting the current flow. Furthermore, this capacity not only decreases the current value that reaches the distant station but tends to further distort the wave, thereby limiting the distance over which satisfactory signals can be sent without additional repeaters.

# TELEGRAPH APPLICATIONS

## 69. Theory of Bridge Polar Duplex for Full Duplex Service

The principle of the polar duplex is based on the theory of the Wheatstone bridge. In Figure 135 let us assume that the winding of a telegraph relay is connected to a Wheatstone bridge which is balanced to determine the resistance of the relay winding. It will be found that upon opening and closing the battery key the telegraph relay will operate, but the galvanometer needle will remain stationery because the bridge is balanced.

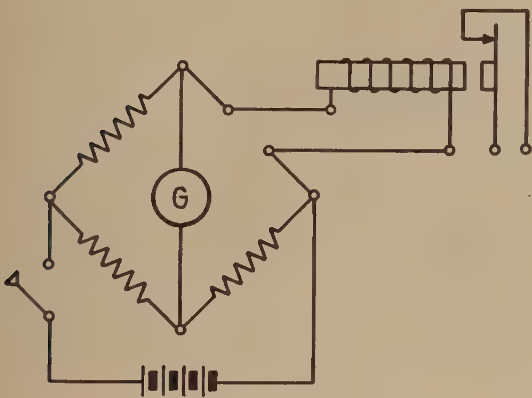



*Figure 135*

Now let us imagine a telephone circuit between two stations with a ground on one conductor at its middle point. The testboard man at the west station connects his Wheatstone bridge to the circuit for making a location of the ground by the Varley method. Let us suppose the testboard man at the east station instead of crossing the circuit for this test, likewise and at the same time connects his Wheatstone bridge for making the same test. The connections will be those shown by Figure 136.

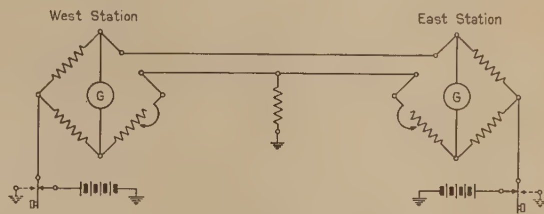



*Figure 136*

**Now if the man at the west station secures a bridge balance, his variable resistance will represent the resistance of the line loop from the ground to the distant station in series with a definite resistance value corresponding to the resistance of the bridge at the east station considered as a complicated network.** In so far as the current flowing through the east network from the west station is concerned, it will be slightly greater with the east battery key closed than with it open, but with a very simple modification of the bridge consisting of a ground connection to the back contact of the battery key (which will not interfere with its use as a bridge) **this current will be the same when the battery key is closed as when open.** Therefore, when the man at the

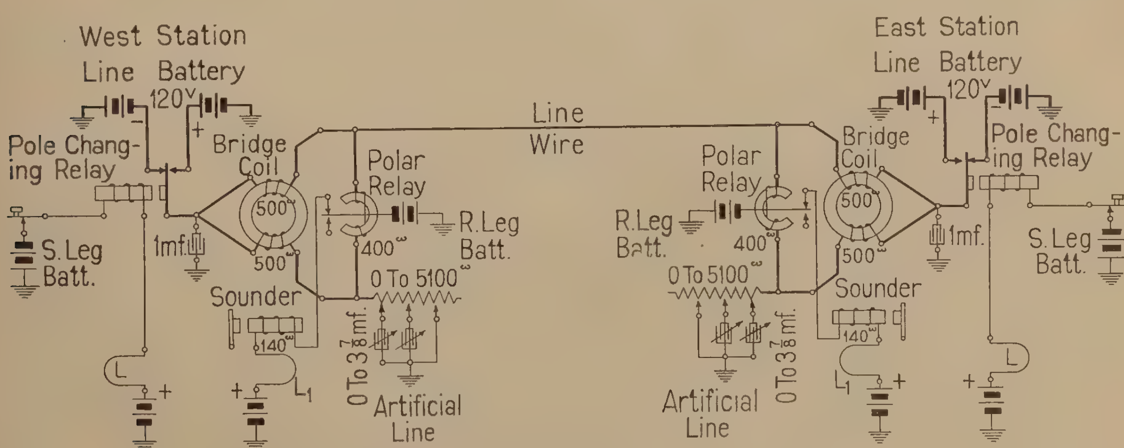



*Fig. 137—Polar Duplex Sets Arranged for Duplex Service.*

west station secures a balance, his own galvanometer will not respond to the opening and closing of his own battery key, but the galvanometer at the east station will receive a current flow due to the closing of this key and will deflect for the same reason that the relay operates in Figure 135. On the other hand, with a similar arrangement of the bridge at the east station, there is no reason why this testboard man cannot secure a balance for his bridge in the same manner as the west station testboard man. **With the two bridges thus balanced one station has control over the galvanometer of the other but has no control over its own galvanometer.** Consequently, the keys at both stations can be opened and closed at the same instant, and the operation in one direction will not interfere with the operation in the other direction. If the galvanometers are now replaced with sensitive relays and the battery keys replaced with telegraph keys, these stations can communicate with each other and send telegraph messages simultaneously. One station cannot "break" the other, however, any more than one station can "break" the other in the arrangement shown by Figure 121. This is called "full duplex telegraph service", and the Wheatstone bridge arrangement shown by Figure 136 is fundamentally the principle of the polar duplex. But instead of using two wires with a ground at the middle point, the second or defective wire is replaced with an artificial line to ground at each station. This artificial line takes the place of the grounded wire as well as the resistance "R" of the variable arm of the Wheatstone bridge.

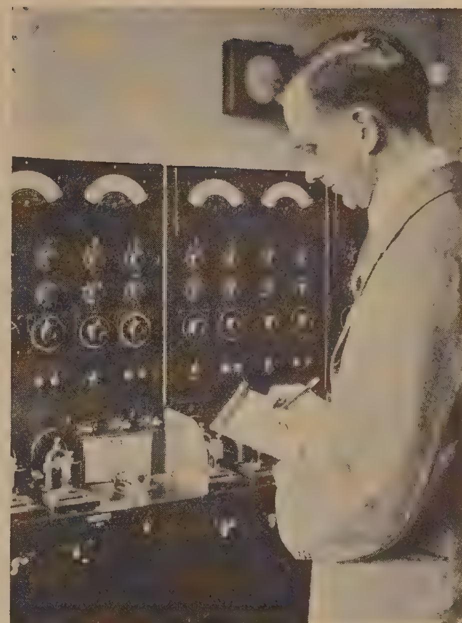
Figure 137 shows a telegraph wire equipped at each end with a simplified polar duplex circuit, and arranged for "full" duplex service. Here we have the more fundamental modifications which adapt the Wheatstone bridge principle to actual telegraph service. Instead of the bridge arms consisting of simple non-inductive resistances two accurately balanced windings of a 5-U retardation coil are employed. Each winding gives an inductance of three to four Henrys to the current in the arm, but when the two windings are in series, i.e., when they are considered as a shunt around the bridged relay (which corresponds to a galvanometer) the coil has an inductance of from 12 to 15 Henrys. The artificial line already mentioned consists of a 0—5100 ohm rheostat which can be grounded, first, directly at any point, thereby simulating the resistance of the circuit grounded at the distant end as well as through any intermediate shunt leakages; and second through two variable capacities at two other points, thus simulating the actual capacity of the wire to ground. Together the adjustments are such that the artificial line is almost identical electrically to the actual wire with another set at the distant end. Instead of a telegraph key in the main battery connection to the bridge the key is inserted in a local battery circuit through the winding of a "pole changing" relay, and the front and back contacts of the armature of this relay are connected to batteries of opposite polarity instead of to battery and ground, respectively. This battery arrangement gives an actual flow of current during the space interval but in the opposite direction to the flow which makes (or "marks") a signal. Further, with a polarized relay for receiving the signal at the distant end, improvements in telegraph transmission are obtained. To prevent excessive sparking at the contacts of the pole changing relay and to reduce the interference to the telephone circuit, a 1 mf. condenser is connected to ground and shunts either contact of the relay. The "polarized" relay mentioned above has a split magnetic circuit completed through the armature causing the armature to be attracted either to one contact or the other and to remain in contact until the current in the winding is reversed. This relay is known as the 30-A and has a normal operating current of .01 ampere.

Full duplex operation naturally calls for two "local" circuits. The one which is called the "sending leg" we have already described as consisting of a key in series with the winding of the pole changing relay. It also includes the telegraph subscriber's loop (or loops) in series, which is used for sending only. The other is called the "receiving leg" circuit and is operated off the contacts of the 30-A polar relay. It consists of the subscriber's receiving loop, with a telegraph relay and its sounder circuit;—the key, while provided, is of course not required for operation.

Other features of the duplex circuit will be described after taking up the theory of "half duplex" operation.

### 70. Theory of Bridge Polar Duplex for Half Duplex Service

The duplex set may be used as a telegraph repeater on the "ordinary" telegraph circuit where the simultaneous transmission of messages in both directions is not desired and the feature whereby one operator may "break" another is incorporated. It is quickly converted from one type to the other by the operation of certain switches, and when arranged for "half duplex" service the circuit is as shown by Figure 138. Here in the receiving leg circuit, the winding of an additional relay having two sets of contacts and known as the "control relay" is substituted for the receiving loop. One set of its contacts is connected into the sending circuit, thereby permitting an incoming signal to "break" the outgoing signal. As is the case with the neutral repeater, this requires a holding coil feature associated with the pole changing relay **in order that the circuit, when opened by the control relay instead of the sending key, will not permit the pole changing relay armature to fall back,** thereby sending over the line a current corresponding to "space" which would "break" the operator at the distant station. The second set of contacts on the control relay shunts the holding coil so that "breaking" with the key of the sending leg is permitted when the control relay is closed. In order that this "break" may be quickened in case the distant sta-



## TELEGRAPH REPEATERS

*Left above*—Typical installation of bridge polar duplex repeaters.

*Right above*—Close-up of metallic repeater sets.

*Below*—General view of metallic telegraph repeaters in cable repeater station.

tion is sending a series of dots that may not let the control relay armature fall back sufficiently to entirely release the holding coil shunt, the lever of the sounder associated with the pole changing relay has a special contact which on the upward stroke shunts the contacts of the receiving relay (polar relay).

In so far as the transmission over the line wire is concerned, half duplex operation is not essentially different from full duplex operation excepting that only one series of signals is being transmitted at any instant.

of an intermediate repeater. When so used for full duplex service, it is only necessary to connect the sending leg of the west set to the receiving leg of the east set and vice versa, as illustrated by Figure 139-A. When so used for half duplex service, it is only necessary for the sending legs to be in series, as illustrated by Figure 139-B. For this latter service, however, it frequently happens that the layout may consist of a number of branches at various repeater points instead of a direct telegraph circuit between two distant stations. In this case it is necessary for all sets at any one station to have their sending legs connected in series as illustrated

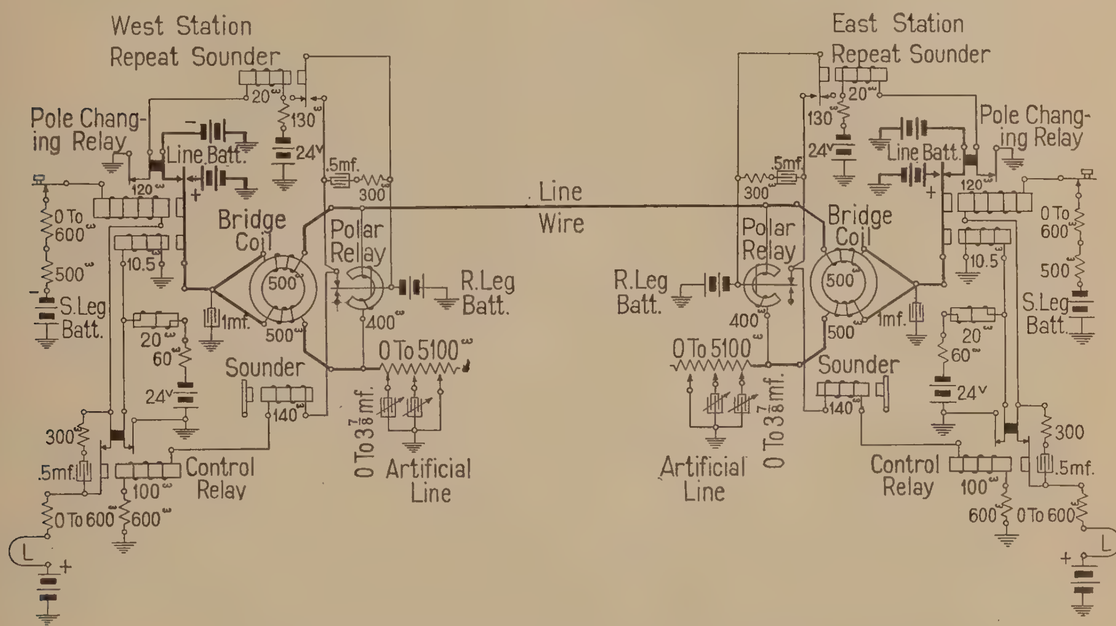



*Fig. 138—Polar Duplex Sets Arranged for Half Duplex Service.*

## 71. Use of Duplex Set as Intermediate Repeater

In the foregoing we have described the duplex set circuit as a terminal set for a line wire. At the terminal points the subscribers' loops for full duplex service can be connected in series with the sending leg and receiving leg, as indicated by L and $L_1$ of Figure 137, or where the service is half duplex these loops can be connected in series with the single leg called the "dummy" as indicated by L in Figure 138. Each subscriber's loop consists of a pair of cable conductors and all battery connections are made in the telephone office (excepting a local battery which may be required in connection with the subscriber's sounder circuit). But the majority of telegraph circuits are more complicated than merely a wire between two stations equipped with terminal sets providing connections for the terminal subscribers. As in the case of neutral telegraph layouts, intermediate repeaters are required at intervals, and any duplex set can be used as half by Figure 139-C. Also, one side of a neutral repeater can be connected into the sending leg as though it were a subscriber's set, and a branch of the layout worked neutral when desired instead of half duplex.

It is further possible to connect the line wire to a neutral repeater at one station and to a half duplex repeater at the other station, as illustrated by Figure 139-D. In this case the battery at the neutral station is of the same polarity as the "spacing" battery of the duplex set so that the neutral relay will stand open when either key is open and will be operated when both keys are closed. At the duplex set, when both keys are closed, no current flows through the polar relay from the "home" battery since the set is balanced, but current from the distant battery flows through the polar relay in such a direction as to hold its armature closed. When the key at the neutral station is open current from the home battery will flow through the relay

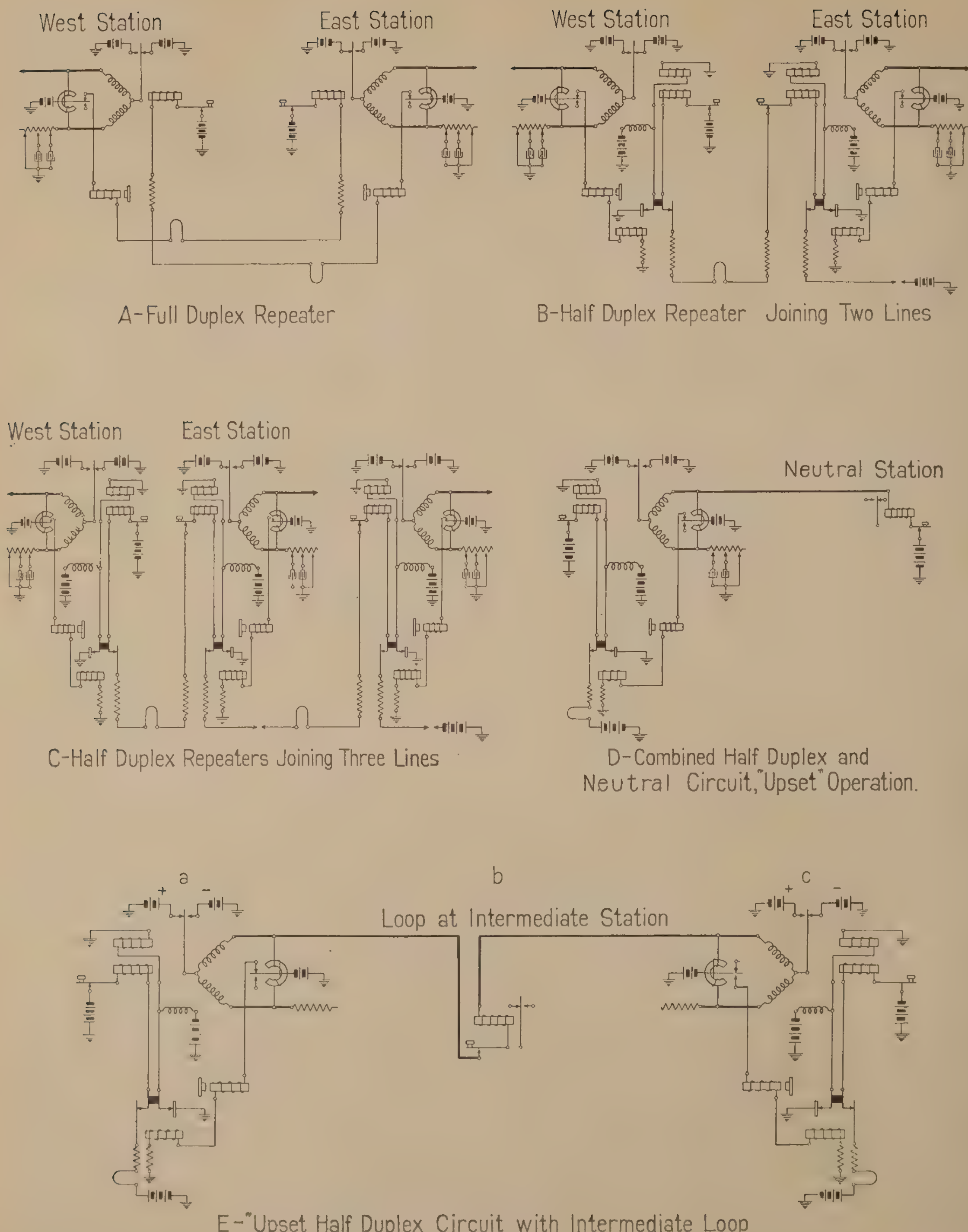



*Fig. 139—Use of Duplex Sets as Repeaters.*

in the opposite direction, thereby producing the space signal.

It is not only possible to operate a neutral station in conjunction with a half duplex, as shown by Figure 139-D, but also when connected at some intermediate point along a wire equipped at both ends with half duplex sets, one of which has its "marking" and "spacing" batteries reversed. This is illustrated by Figure 139-E. Here when sending from the neutral station the opening of the circuit "upsets" the balance of both half duplex sets, thereby simultaneously transmitting the signal in both directions instead of in one direction only, as illustrated by Figure 139-D.

### 72. Other Features of the Duplex Set

Figures 137 and 138 show the circuit of the duplex set both for full duplex operation and half duplex operation in its simplest form. Other features that are incorporated in the circuit and are essential for its efficient operation are omitted for clearness. These are briefly as follows: A number of variable resistances other than the one in the artificial line are used for regulating current values, etc. One such variable resistance is in series with the line wire and a similar identical resistance is in series with the artificial line. These are used for adjusting the line current which should not exceed .075 amperes. They are mounted in a single rheostat box coded the #6-A rheostat. Two other variable resistances are connected in the sending and receiving legs, respectively, for full duplex operation and in series for half duplex operation. These resistances together with the artificial line resistance are mounted in one box which is coded #5-A rheostat. Each of the two variable condensers of the artificial line are arranged to give any value of capacity from ⅛ mf. to 3⅞ mf. by means of a 10-A switch.

When operating a duplex set over a composited wire it is not only necessary for the artificial line to balance the line wire and the series resistance used to regulate the current of the line wire, but it is necessary to balance the composite set as well. This is accomplished by connecting one winding of a 5-AA retard coil, a 6 mf. condenser, and a 2 mf. condenser in series with a resistance, in the artificial line circuit in the same way as the corresponding apparatus is connected in the actual composite set. A 13-A type of switch throws the composite balancing apparatus out of the circuit when the set is being used on a simplexed or other non-composited circuit.

In connection with the "upset" operation of a neutral telegraph repeater at an intermediate station, we have mentioned that it is necessary to reverse the polarities of the batteries at one station and to reverse the direction of current flow through the winding of the polar relay at the other station. This requires two additional features in the duplex set circuit. A #14-A reversing switch is wired between the battery taps and the contacts of the pole changing relay, while a #6007-A reversing key is connected to the line winding of the polar relay.

There is a third lever on the #14-A switch which provides means for connecting the junction point of the bridge to ground through a 150 ohm resistance. This permits a station in case of trouble to check its balance independently of current flow from the distant station, when the switch is operated at that point. This switch is intended, however, for use in case of trouble only and is not ordinarily used when a station is being balanced on a routine basis.

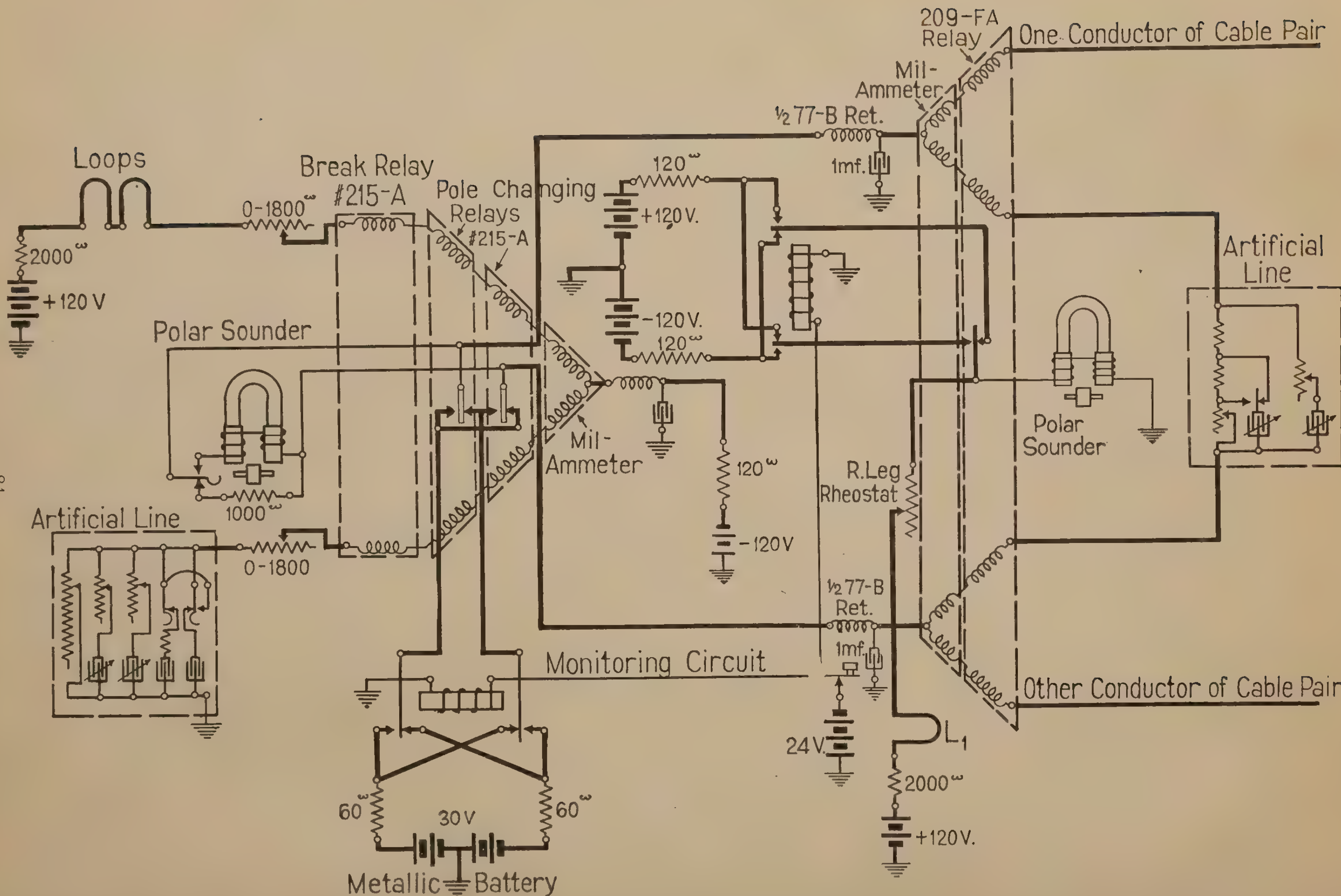
Connected in series with the polar relay is a milammeter used in securing an exact balance at the home station by showing when no current is flowing through the polar relay winding. It further assists in adjusting the capacity of the artificial line to balance that of the actual line, since the "kick" of the needle at the "make" or "break" of the key would indicate unbalance of capacity regardless of whether or not the needle came to rest at zero, indicating balance of resistance. The contacts of the control relay and the polar relay are bridged with non-inductive resistances in series with a .5 mf. condenser to prevent sparking in the same way as the contacts of the neutral repeater relays.

### 73. The Differential Type Duplex Telegraph Repeater

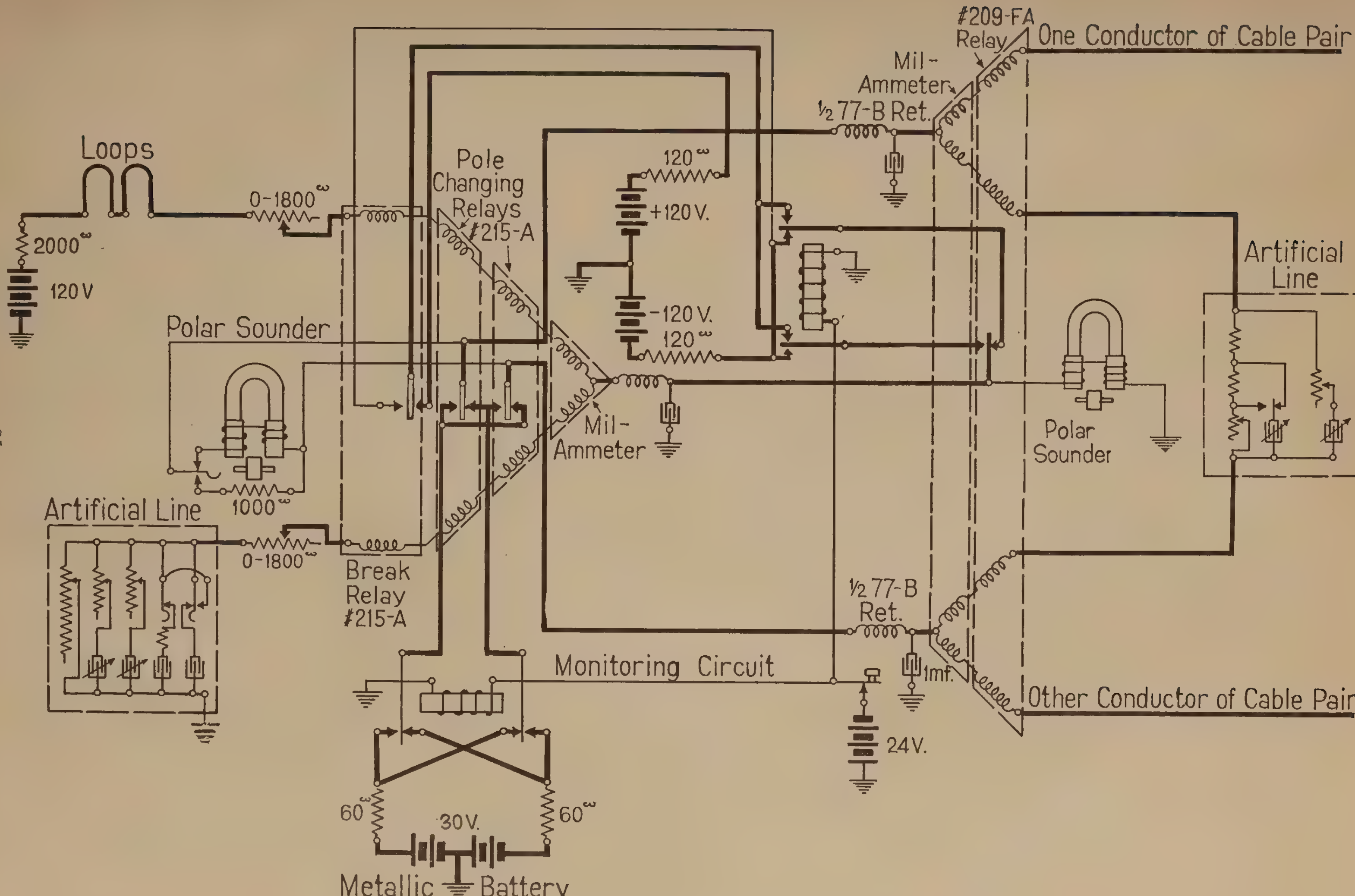
While most duplex sets used for open wire telegraph service in the Bell System are of the bridge type, having the polar relay connected as the galvanometer of a Wheatstone bridge, there is another type in use to some extent for open wire and extensively for cable and carrier sets which employs the "differential" relay principle. In this circuit there is no bridge relay, but a line relay having two identical windings which are connected as the arms of a bridge in the same way as the windings of the 5-U retardation coil. When equal currents are flowing in the two windings, as is the case of the balanced bridge when transmitting, the magnetic circuit in one winding balances that of the other, and we have the same condition as we have in the polar relay for no current flow. But when receiving, the current of the incoming signal flows through the two windings in series with the artificial line, thereby upsetting its magnetic balance in the same way that current flowing through the winding of the polar relay upsets its magnetic balance.

### 74. Advantages of Half Duplex Operation Over Neutral Telegraph Systems

The duplex set arranged for "half duplex" service has marked advantages over the neutral telegraph repeater. It is interesting to study these advantages which are briefly as follows:

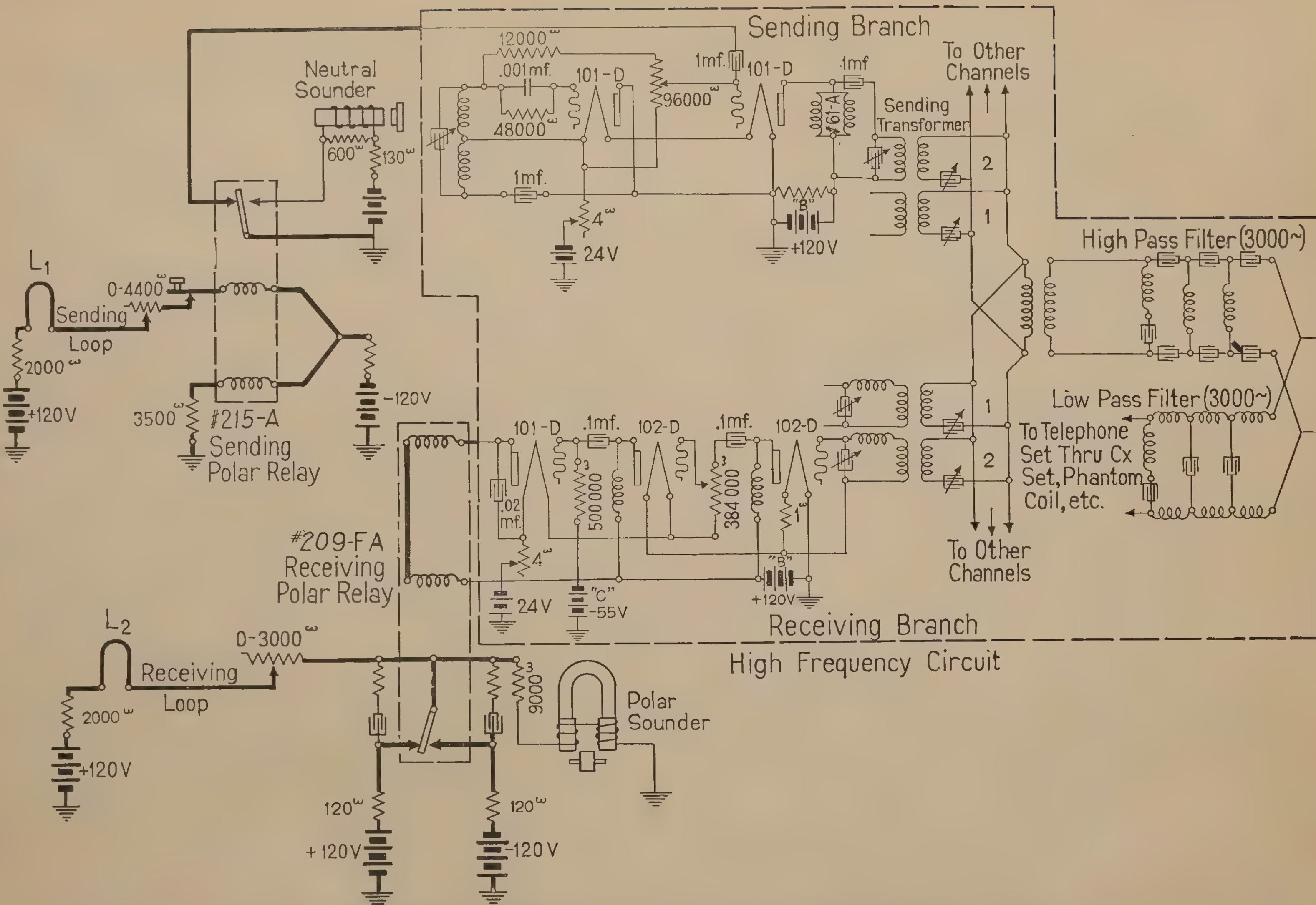



A-Terminal Set Arranged for Full Duplex Service

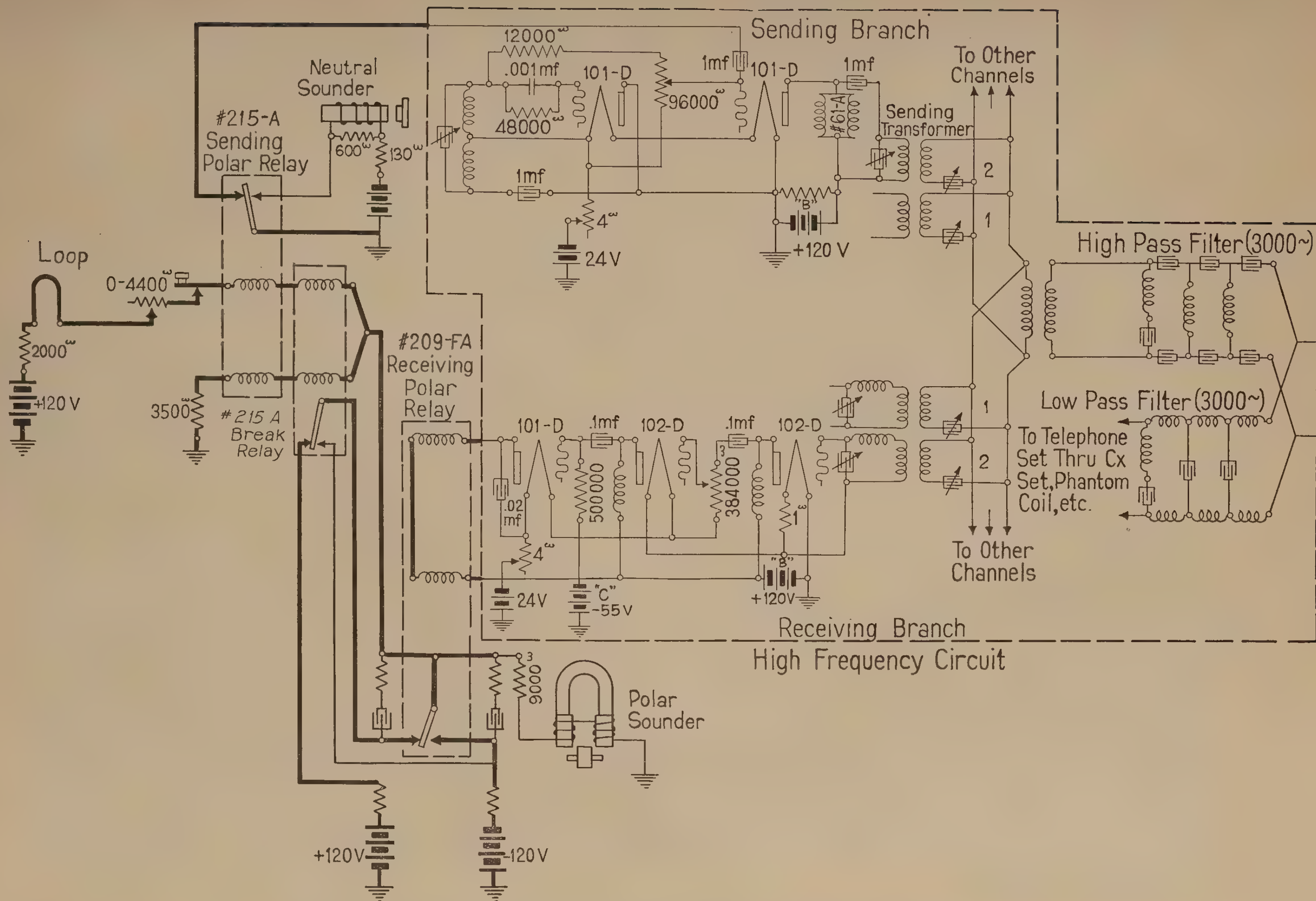



B-Terminal Set Arranged for Half Duplex Service

*Fig. 141—Metallic Telegraph System for Cable Circuits.*




A-Terminal Set Arranged for Full Duplex Service




B-Terminal Set Arranged for Half Duplex Service

*Fig. 142 Carrier Current Telegraph System, Type "B"—Terminal Set Circuits.*

a. The same set can be used either for full duplex or half duplex service, thereby giving flexibility in the number of sets required. (However, this is offset by the higher cost of the set and by the fact that two sets are required at intermediate stations to make one repeater.)

b. The transmission of current for "spacing" gives the effect of increased voltage without increasing the current value in any part of the apparatus or subjecting the circuit to high working voltages that might be unsafe.

c. The balance principle permits satisfactory operation over leaky lines that could not be used in connection with neutral operation.

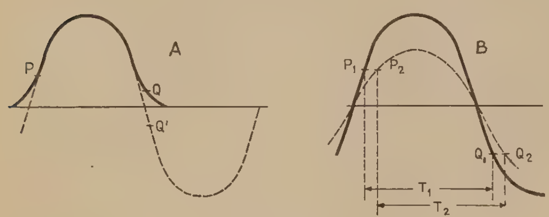



*Figure 140*

We can best understand advantage **b** by referring to Figure 140-A, the heavy line of which shows the current curve for a dot in the neutral telegraph system already illustrated by Figure 127. If we could imagine the spacing signal between this dot and the next dot represented by a negative current pulse below the zero line, we can readily see where the slow "build-up" at the beginning of the signal and the slow "decay" at the end of the signal would be eliminated without appreciably increasing the "maximum" slope of the curve. The dotted line represents such a current curve. The length of the signal for this curve does not depend upon operating and release current values such as "P" and "Q", but since a polar relay is used for receiving would depend upon a positive operating current and a negative operating current such as P and $Q^1$. Since however, any circuit conditions that might affect the shape of the curve for the positive current should likewise affect the shape of the curve for the negative current, the time between the operation of the polar relay in one direction and the operation in the other direction should be more nearly constant than that which is regulated by operating and release currents. This is illustrated by Figure 140-B where $T_1 = T_2$.

The explanation of **c** above can be understood by first referring to Figure 134. If here the east station is sending to the west station, the west station relay will have a definite current flowing through the shunt "S" to ground even while the key at the east station is open. This tends to keep the relay energized at all times, and requires adjustments whereby the release current must be considerably greater than the current flowing through the shunt "S" under this condition. This requires that each relay, when receiving, work as a marginal relay which makes it very difficult to adjust. In half duplex operation there are no such limitations on the polar type receiving relay because it is possible with the artificial line to compensate for any leaks to ground the line wire may have, thereby reducing the effect of the leak to a mere shunting of the energy.

**75. The Metallic Telegraph System for Cable Circuits and the Direct Current Features of the Carrier Current Telegraph Circuit**

Figure 141 is a theory drawing of the cable type telegraph repeater. This illustrates both the full duplex and half duplex circuit for a terminal set. Transmission over the cable is accomplished by a 30-volt metallic battery connected to two equivalent bridge circuits both connecting to an ungrounded artificial line. The bridges work on the "differential" principle. The 209-FA receiving relay has four operating windings, and is in effect, a double differential bridge relay. The grounded side of the repeater likewise employs "differential" relays operating on the balanced bridge principle. Here the sending loop of the "full duplex" and the local loop of the "half duplex" are similar to the upset connection shown by Figure 139-D. The 30-volt sending battery for the cable side of the repeater is associated with a double armature arrangement of two #215-A relays so that the polarity of the metallic battery is reversed instead of connections being made, first to a positive battery and then to a negative battery as is the case with the open wire duplex system. This permits the ground to be removed from the metallic battery in case earth currents seriously interfere with the proper operation of the system. Instead of having a key in the sending leg for the monitoring operator to "break", there is a separate monitoring circuit equipped with relays for reversing the polarity of the batteries in both directions. This results in a closed key at either end making a "space" instead of a "mark" signal and a break is thereby transmitted. The sounder associated with the metallic line sending is equipped with a horseshoe magnet, thereby converting it to a polar type that will operate directly from reversals of battery polarity instead of from contacts that alternately open and close the circuit. In "half duplex" operation a special "break relay" of the same type as the pole changing relays is operated differentially and is connected in series with the pole changing relays. This permits the subscriber to transmit a "clean cut" break by insuring that the armatures of the pole changing relays once shifted by the "upset" remain so shifted, preventing the reversals of current which otherwise would occur when the 209-FA relay responds to signals from the distant end.

With the exception of the foregoing, it is seen that the circuit theory of the metallic telegraph system is not essentially different from the duplex system used for open wire lines. The apparatus

and general assembly, however, are a more radical departure from the older practices. The low line current employed requires very sensitive apparatus and the #209-FA relay in particular is a most unique type in this respect. In addition to its operating windings it has two others which are used as a vibrating circuit, thereby increasing its sensitivity. None of the relays are adjusted during operation but by means of spring contacts can be quickly removed for adjustments of a somewhat laboratory nature while spares are substituted in the set.

On account of the large number of metallic telegraph sets required in connection with the cable plant, two terminal sets are not depended upon for each intermediate repeater. A simpler repeater circuit, whereby two #209-FA relays are employed in each direction, entirely eliminates the "grounded line" at intermediate cable points. In this repeater the 30-volt metallic battery connections are made directly to the contacts of these #209-FA relays.

The D. C. features of the carrier repeater are very similar to the corresponding parts of the metallic cable system but are much simpler, since the line balance is taken care of in the high frequency equipment. Figure 142 shows in heavy lines simplified diagrams of these D. C. features and shows in lighter lines a schematic of the high frequency equipment which, however, can be analyzed only after a study of vacuum tube circuits and high frequency alternating current transmission.

# CHAPTER XIII

## TELEPHONE APPARATUS AND CIRCUITS

### 76. The Telephone Receiver

The next subject for consideration in our study of electricity would logically be that of the theory of alternating currents, but before going into that it may be profitable to devote a Chapter to some discussion of certain of the more common and relatively simple types of apparatus used in telephone work and to illustrate how apparatus units are connected together to form working circuits. It is obviously impossible, however, to describe more than a very few of the many different kinds of apparatus used or to analyze the operation of any large number of the variety of circuit assemblies, each designed to perform some definite function, that are standard.

mechanically fastened to the magnets near the windings, the air gap between the pole pieces and the diaphragm is accurately gauged and a considerable part of the variation in this air gap due to contraction and expansion at different temperatures is eliminated. The brass cup also affords a dust proof case for the windings. The direct current resistance of the two windings (in series) is approximately 80 ohms.

In the manufacture of this instrument, the shell and cap are made of very hard rubber stock, and after being highly polished, are accurately gauged for the proper dimensions. The horseshoe magnet is made by welding two bars of special steel into the U shape. It is later inserted across two pointed

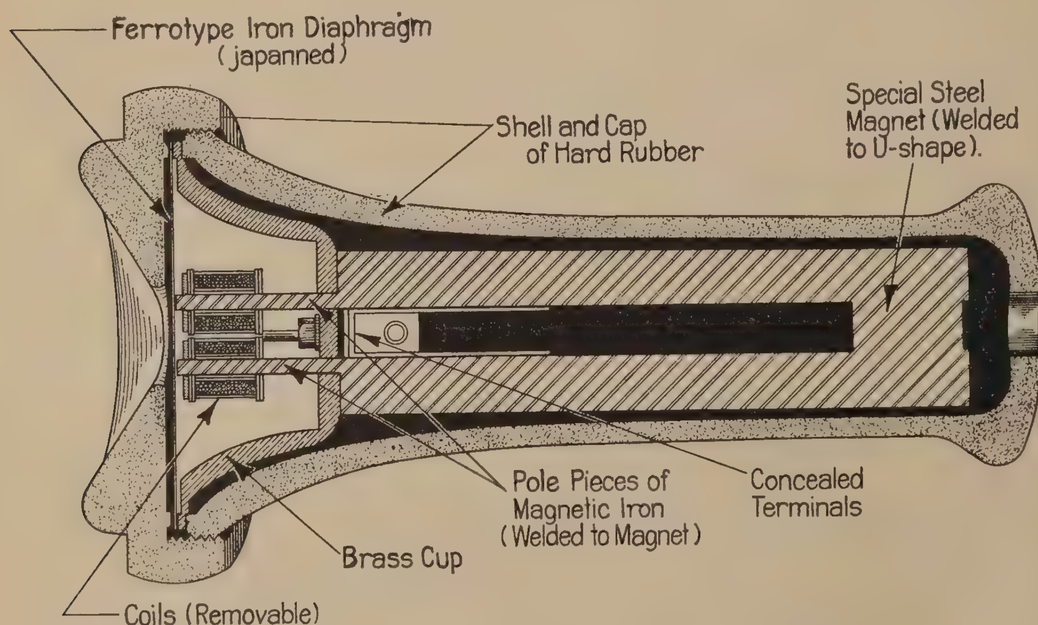



*Fig. 143—Cross-Section of No. 144 Receiver.*

As the first devised and perhaps most fundamental of telephone apparatus units, we may consider the telephone receiver. Figure 143 shows the mechanical construction of a modern type of receiver for substation use which has certain refinements in design that are marked improvements over earlier types.

The concealed binding posts eliminate the possibility of shocks to subscribers and protect the cord connection against shorts, opens and grounds. The hard rubber shell and cap are both changeable parts, being easily replaced. Since the brass cup is metal pole pieces of a powerful electromagnet and given a high degree of magnetization. The coils are wound into longitudinally shaped spools and pressed on the magnet pole pieces. The brass cup is drawn from sheet brass by a punching and annealing process.

Other than the #144, the most important type of telephone receiver, which is used generally, is the #528 (watch case type) now standard for operators' telephone sets. It has a metal case with hard rubber cap. The operators' telephone sets, on the #4 type testboard, are equipped with a special high

resistance receiver in a green finished metal case, which is coded #525 and is wound to a direct current resistance of about 500 ohms. It is used in connection with the testing circuit in preference to other types of operators' head set receivers since the high resistance permits it to be bridged across a talking connection without appreciable transmission loss.

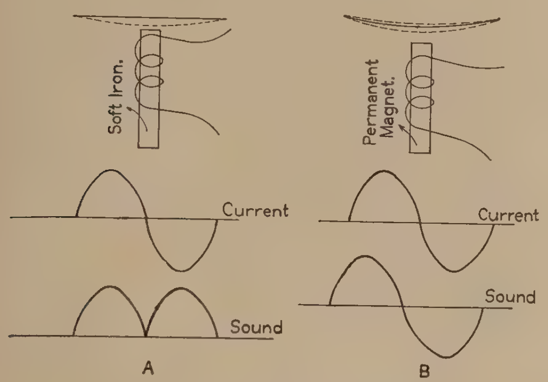



*Fig. 144—Action of Receiver.*

The above types of telephone receivers are equipped with permanent horseshoe magnets, and it is important that the magnetism should not be impaired by jarring or other abuse. A permanent magnet not only increases the amplitude of vibration of the diaphragm when the voice current is flowing through the windings, but prevents the diaphragm vibrating at twice the voice frequency.

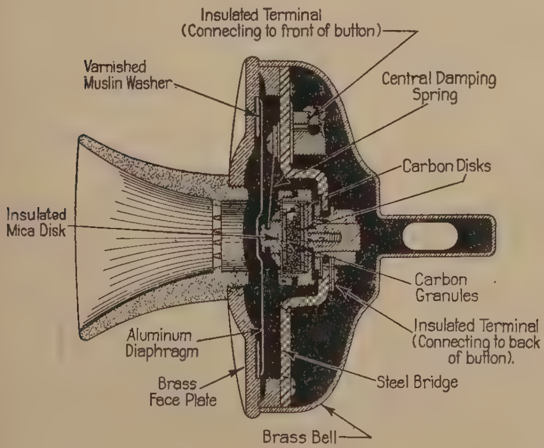



*Fig. 145—Cross-Section of No. 323 Transmitter.*

This principle is illustrated by Figure 144. When a piece of soft iron is held near an electromagnet, it is attracted by the magnet regardless of which direction the current is flowing through the windings. Thus, an alternating current through a winding having a soft core instead of a permanent magnet will assert an attraction during each half cycle, which in case of the receiver diaphragm will establish a vibration, with a frequency twice that of the current. If, on the other hand, a permanent magnet is used, the alternating current establishes a vibration of the same frequency by merely increasing or lessening the pull already exerted on the diaphragm.

## 77. The Telephone Transmitter

A cross-section of the working parts of a #323 type transmitter is shown in Figure 145. This instrument has certain improved transmission features over the #329, and differs from earlier types such as the #229 for general substation use in that it is an insulated type with no terminal grounded to the frame. This construction prevents shocks to the user and lessens the possibility of induction due to crosstalk from other lines. The top terminal shown in the figure engages the tip of one cord by means of a set screw, and connects to the front carbon disc of the transmitter button by means of the central damping spring which

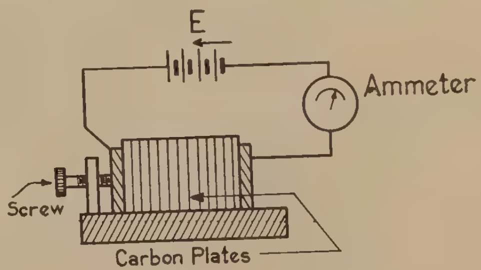



*Figure 146*

is held by an insulated screw through the steel bridge. The other terminal connects to the rear of the button through the button's mounting which is insulated from the steel bridge by means of mica. The vibration of the insulated diaphragm is transmitted directly to the front carbon disc through its pressure contact against the small piece of metal secured to the disc. This causes a variation in the pressure on the carbon granules which varies their resistance in a manner that may be better understood by referring to Figure 146. Here is shown a series of carbon plates in contact with each other and under compression by a screw clamp. If a battery E in series with an ammeter is connected across the group of plates, the current is seen to vary considerably with very small adjustments of the screw. This property of carbon is amplified in the transmitter button by using carbon granules between the carbon discs. The resistance of the carbon in the transmitter is approximately 50 ohms but decreases due to heating when the current is allowed to flow through the transmitter button for long periods.

A few other types of transmitters in use are the #232, a hanging type for testboards, the #234 which is the operator's breast transmitter, and the #266, especially designed for linemen's test sets.

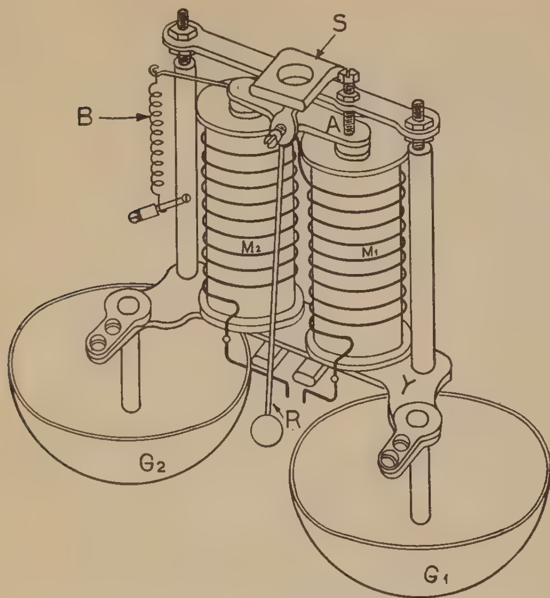



*Fig. 147—Polarized Ringer.*

### 78. The Polarized Ringer

The proper name for the substation telephone bell is "ringer". Figure 147 illustrates one type of ringer that is standard in the Bell System and is used on the majority of subsets. It is designed to operate on 20-cycle alternating current or on 20-cycle pulsating current when adjusted by means of the biasing spring. It consists of two electromagnets, $M_1$ and $M_2$, which are mounted on the soft iron yoke Y. The armature A is pivoted so as to give a slight air gap separation between its two ends and the respective cores of the magnets. The tapper rod R is securely fastened to this armature. One end of the permanent steel magnet S is mounted near the middle of the yoke Y, and the other, or north, end of the steel magnet is sufficiently near the armature that the magnetic circuit established by the permanent magnet is split at the north pole and carried through the armature and soft cores of the magnets to the soft iron yoke Y. The lines of force unite here and return to the south pole of the magnet which is secured to the center of the yoke. The electromagnets are in series and when an alternating current flows through their windings, the magnetism established by the permanent magnet will be strengthened during the first half cycle as it flows through one coil and weakened by an equal amount in the other. This will increase the attraction of the first core for the armature and decrease that of the second, thereby permitting the tapper to strike one gong. When the current reverses during the second half cycle, the attraction is reversed and the tapper strikes the other gong. Thus, the tapper will strike each gong 20 times per second.

If the biasing spring B is tightened (other than with slight tension to prevent tapping due to the rush of the direct current when the operator sticks the plug in the line jack), the bell will respond to pulsating current instead of alternating current, as explained in Chapter X.

### 79. Plugs, Jacks and Cords

Plugs, jacks and cords are used in telephone work as a means of performing switching operations rapidly and with a maximum of flexibility. In addition to facilitating direct connections, jacks may be arranged for automatically accomplishing other

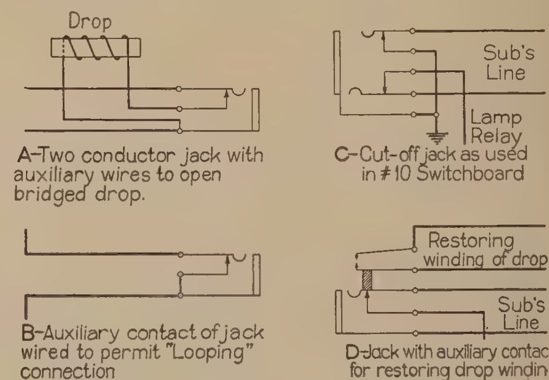



*Fig. 148—Various Uses of Auxiliary Contacts of Jacks.*

circuit operations by equipping them with auxiliary springs. A few such arrangements are shown by Figure 148. The simple manner in which the signalling drop of a line terminating at a telephone switchboard can be opened so as not to impair transmission when a plug is inserted in the jack is illustrated by Figure 148-A. Figure 148-B shows another use of the same auxiliary contact. Here a telegraph set terminated with a two-conductor plug may be looped in series with the wire at a single operation, or an ammeter connected to a cord may be inserted for measuring the current in the wire. Figure 148-C illustrates the use of normals for two springs of a three-conductor jack such as is used in connection with the #10 local switchboard to perform a function similar to that of the cut-off relay in the #1 switchboard. Figure 148-D illustrates another commonly used two-conductor jack which in this case is wired to operate a self-restoring drop in the same way as the three-conductor jack shown in Figure 112.

The mechanical construction of a few types of jacks used at the present time in connection with long distance service, is illustrated by Figure 149.

The #49 jack is mounted in strips of 5, 10 or 20 for use in the face of both local and toll switchboards. It takes the #110 plug. A smaller jack, coded as the #92, takes the #109 plug, and is used in the face of larger switchboards where the multiple must accommodate a greater number of lines than the toll or small local switchboard multiple. The #99 jack, illustrated in the same figure, is mounted in pairs in the switchboard key shelf to take a #137 plug, in which is terminated the operator's breast transmitter and head receiver. The remaining jacks in Figure 149 are those commonly used in the #4 and #5 toll testboards, and other testroom equipment requiring numerous combinations of auxiliary contacts. They can be mounted either singly or in pairs to accommodate single one or two conductor plugs such as the #116 and #47 or 2, 3 or 4 conductor plugs such as the #43, #241 and #137 types, respectively. Jacks of this type are made with a sherardized metal frame having a brass sleeve mechanically fastened to its front face. The channel shape readily permits the mounting of German Silver contact or auxiliary springs properly insulated from each other by bushings and washers.

Figure 150 illustrates both the mechanical and electrical features of various plugs and Figure 151 shows the construction of a commonly used type of switchboard cord. While this is only one of many cords in use, it represents the standard features and gives an insight into cord manufacturing processes.

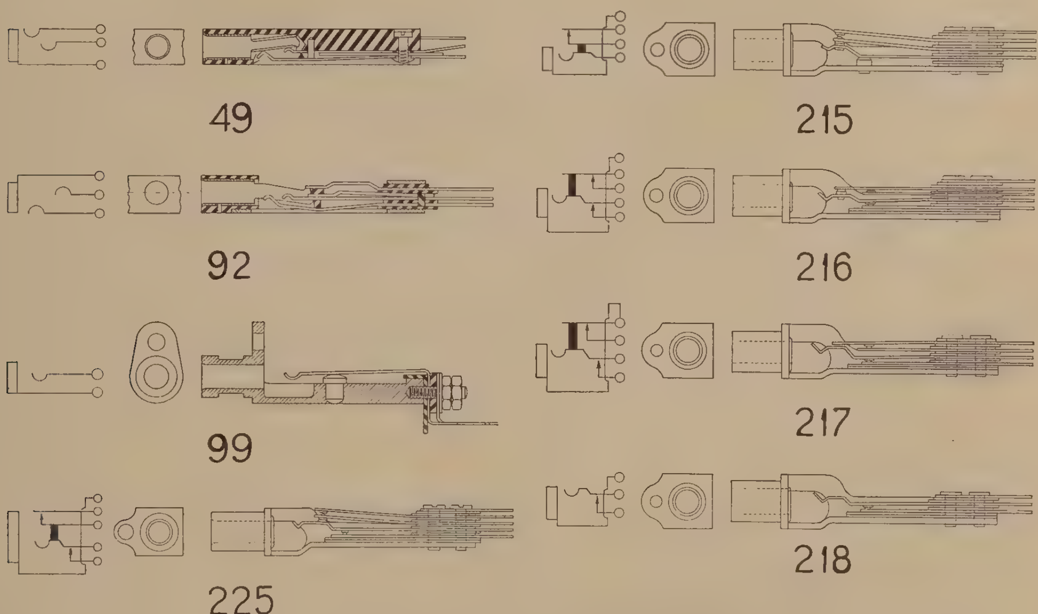


*Fig.149—Jacks used in Connection with Long Distance Service.*

## 80. Resistances

No single unit of apparatus is more fundamental than the resistance, several types of which have countless uses in the telephone plant. Testing apparatus, such as the Wheatstone bridge, ordinarily uses plain spool type resistances which consist of German Silver wire of suitable current carrying capacity (gauge) wound on a wooden spool, as in Figure 152. The resistance is made "non-inductive" (that is, will not induce potentials in adjacent spools or other electrical conductors) by winding simultaneously two conductors instead of one, with the two conductors short-circuited at one end and used as the resistance terminals at the other.

Two more common types of resistances which are used for such purposes as regulating the current from 24-volt battery at Central Offices to the proper value for operating and releasing relays, lighting switchboard lamps, etc., are illustrated by Figure 153. They are coded as #18 and #19, the #18-type being a single plain resistance, and the #19-type having a third connection to an intermediate point of the resistance winding. Both types are furnished with resistance values ranging from less than one ohm to a few thousand ohms. The accuracy is ordinarily within 5%, and the safe radiating capacity, which depends upon the mechanical design rather than the resistance value, is approximately 5 watts. On account of the flat shape, the winding is practically non-inductive. It consists of

bare special high resistance wire covered with micanite. The ends of the wires are brought out to the metal terminals which give mechanical reinforcement to the edges. These terminals are 1-5/16 inches between centers, and are equipped with two clamping nuts and fibre washers for mounting on a standard iron mounting plate, which will accommodate from 10 to 40 resistances.

Figure 155 illustrates the Lavite resistance which has a very high resistance value for a comparatively few turns and for this reason is practically non-inductive. This type is made in units of 12,000, 24,000, 48,000 and 96,000 ohms. Its principal use is in connection with vacuum tube circuits such as telephone repeater potentiometers, etc.

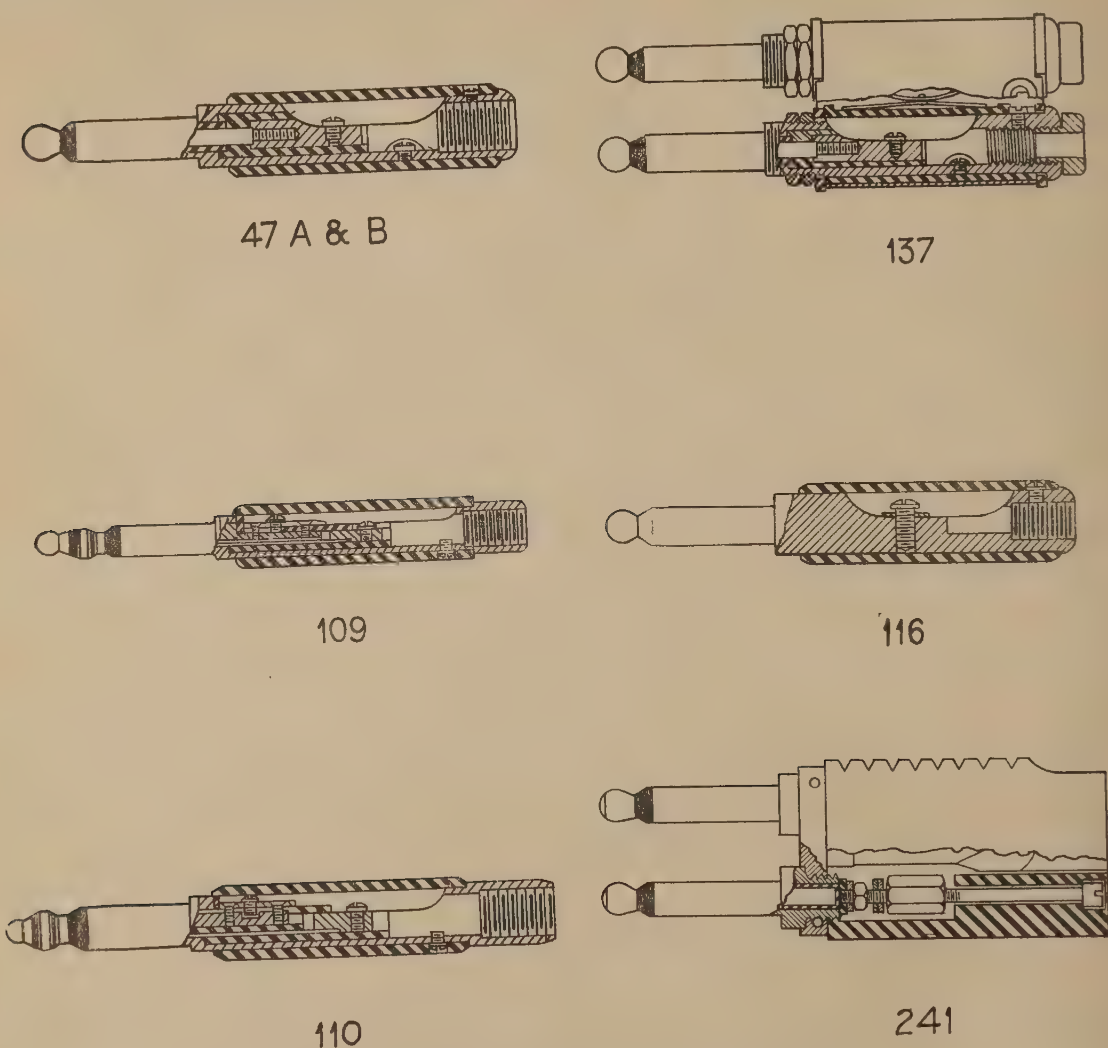



*Fig. 150—Plugs used in connection with Long Distance Service.*

When it is necessary for a resistance to radiate heat energy greater than 5 watts, the vitrohm type is used in preference to the #18 or #19 type. Ordinarily these resistance units are equipped with an Edison base (lamp-socket screw) for mounting in receptacles on slate panels, as illustrated in Figure 154. The safe radiating capacity of this type is approximately 60 watts, or about 12 times that of the #18-type.

When a series of resistances is used in connection with adjustable dials, such as those of a Wheatstone bridge, it is not always necessary to have 10 separate units for each dial. Figure 156 shows several commonly used schemes of dial connections, one of which gives steps of zero to nine with only four spools. An adjustable dial, such as this or any one of the devices shown in Figure 157 for adjusting a resistance value, is called a rheostat". If a rheo-

stat is connected as shown in Figure 158 so as to give an adjustable E.M.F., it is called a "potentiometer".

### 81. Switchboard Keys

A telephone key is a circuit opening or closing device or a special kind of switch adapted to telephone circuits. The way in which a simple six-spring key may perform the same circuit functions as the double pole, double throw switch, was illustrated in Figure 6. Just as plugs, jacks and cords provide more flexible and more complicated connections than can be provided with older type switchboards, the key has many advantages over the knife switch and facilitates additional features essential to telephone operation. Contacts to be made or broken may be delicately adjusted through the use of German Silver springs. These contacts, which are adequate for carrying the current values

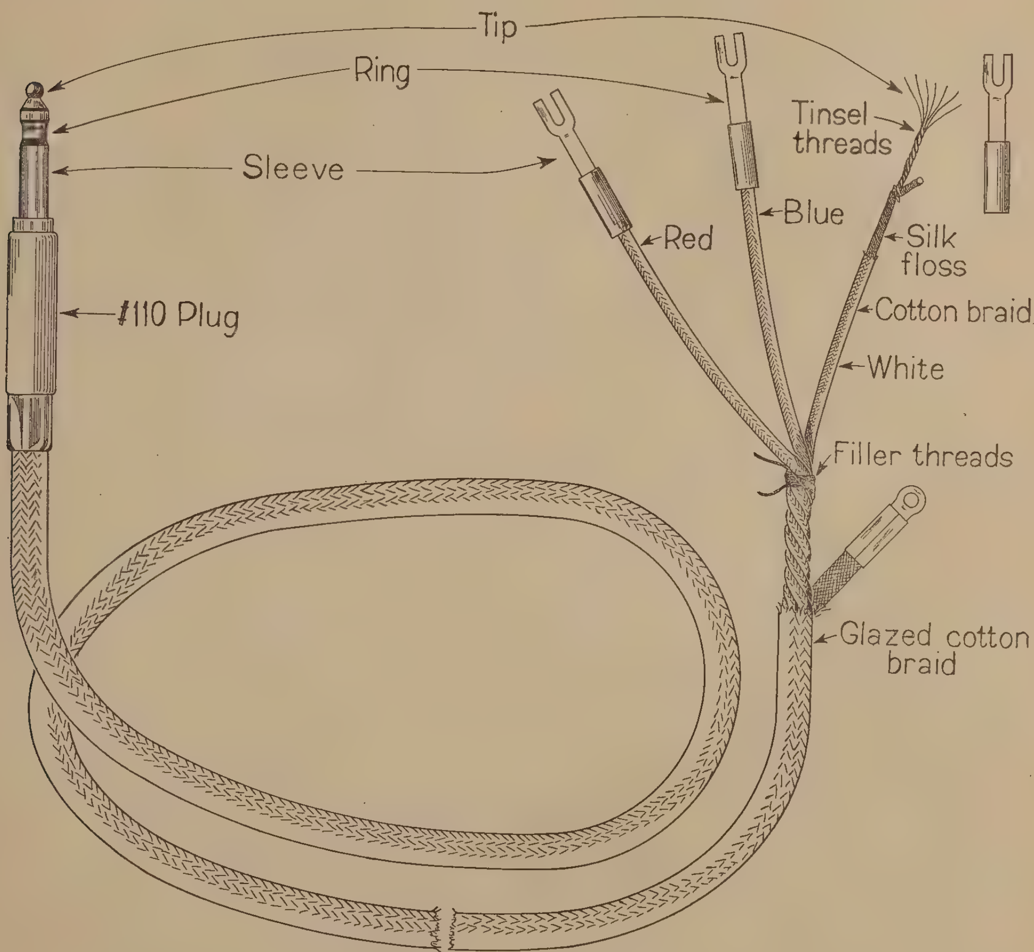



*Fig. 151—Switchboard Cord.*

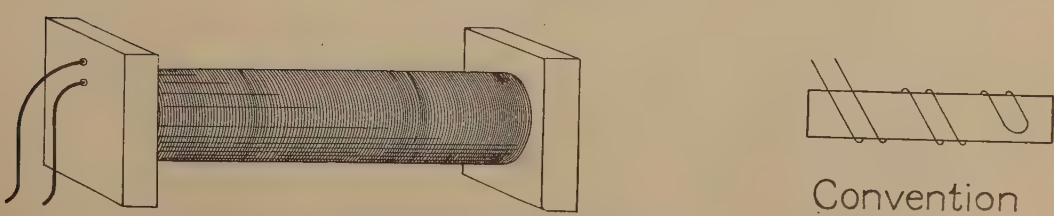



*Fig. 152—Plain Spool Resistance.*

ordinarily used by telephone circuits, are made through special contact metal welded to the German Silver springs, thereby preventing excessive resistances from being inserted in the sensitive telephone circuits. Auxiliary contact springs permit the operation of additional or more complicated circuit features which could not be easily provided on any other form of switch.

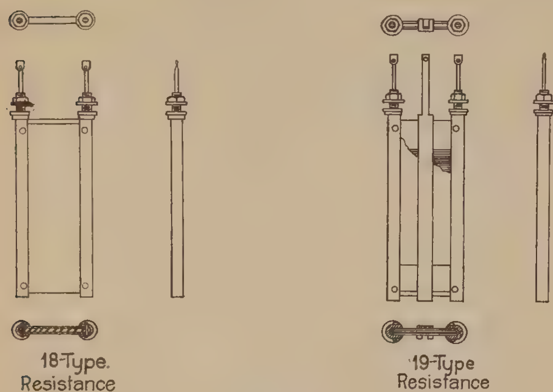



*Figure 153*

*Figure 154*
*Vitrohm Resistance.*

*Figure 155*
*Lavite Resistance.*

Figures 159 and 160 illustrate two designs of keys used in the operation of switchboard circuits which are especially important. Both are used in connection with the line position toll operator's cord circuit. As will be observed from the lever arrangement and the conventions showing the contacts, the two types are identical in so far as their operation and circuit features are concerned, but the #463-C key (Figure 159) differs from the #AIA key (Figure 160) in that it is an older type having a different arrangement of springs. The #AIA key was designed for use in connection with the universal key shelf and has the so-called "unit" construction. This permits one or more key spring units to be mounted, as illustrated, on a standard metal base which is equipped with a hard rubber top. Two types of spring units are provided, the lever type (Figure 160) and the push button type. The convenient manner in which individual units can be removed, and in which any key combination can be had by selecting various units for one standard base, has certain maintenance advantages.

## 82. Relays

A relay may be defined as an electrically operated switch or key. It gives one electrical circuit control over one or more other electrical circuits, or as in the case of the locking type relay, may have certain control over the same circuit. There are several thousand types of relays manufactured by the Western Electric Company and classified according to their mechanical construction features, number of windings, resistance of windings, number and kinds of contacts, whether contacts are made, broken or switched and the order in which they are made, speed of operation and current values required for operation. For our purposes, we may study a few general types of relays, remembering that minor changes in the electrical design of each type provide another of the same series which may be adapted to a widely different use.

Probably the earliest use of the relay was for telegraph circuits. A modern telegraph relay is illustrated by Figure 161. Its function is to operate a telegraph sounder connected to a local battery through its contact points, which requires more energy than is present in the telegraph line wire. It also permits some adjustment of the telegraph signals. This is effected by the retractile spring connected to the release armature and the air gap between the armature and pole pieces. These adjustments can be made by screws $S_1$ and $S_2$, respectively. Figure 162 shows a standard type of telephone relay, known as the "A" type, which is used as a line relay and as a "cut-off" relay for common battery subscribers' circuits (see Figure 113—Relays "A" and "B"). The mechanical construction of the "A" type relay is unique in several respects. In dimensions it is both small and narrow, thereby permitting a large number to be mounted in a comparatively small space, which results in a great saving of relay rack space in local central offices where a large number of line and cut-off relays are in use. The soft iron armature forms a loop which completes the magnetic circuit from the core through the two halves of the loop, and mechanically operates the contact springs. The winding is of enamel insulated small wire which aids in reducing the size of the relay. The "A" type is very quick in operation, and gives a "flashing line lamp" for more rapid moving of the hook-switch than was possible with earlier types. These relays are ordinarily mounted on complete strips of 20 and a single cover encloses the entire strip.

The "B" type relay, illustrated in Figure 163, is in many respects similar to the "A" type and is used as a supervisory relay (Figure 113—Relay "C" in the local cord circuit). Unlike the "A" type it has an individual cover and thus requires more mounting space.

A type of relay somewhat more elaborate than either the "A" or "B" but having in many respects similar mechanical construction, is known as the "E" series. It facilitates numerous combinations of contact springs and is adapted for very general use in telephone circuits. It is illustrated by Figure 164. It can be mounted either 10 per strip with individual covers or 20 per strip with an overall strip cover.

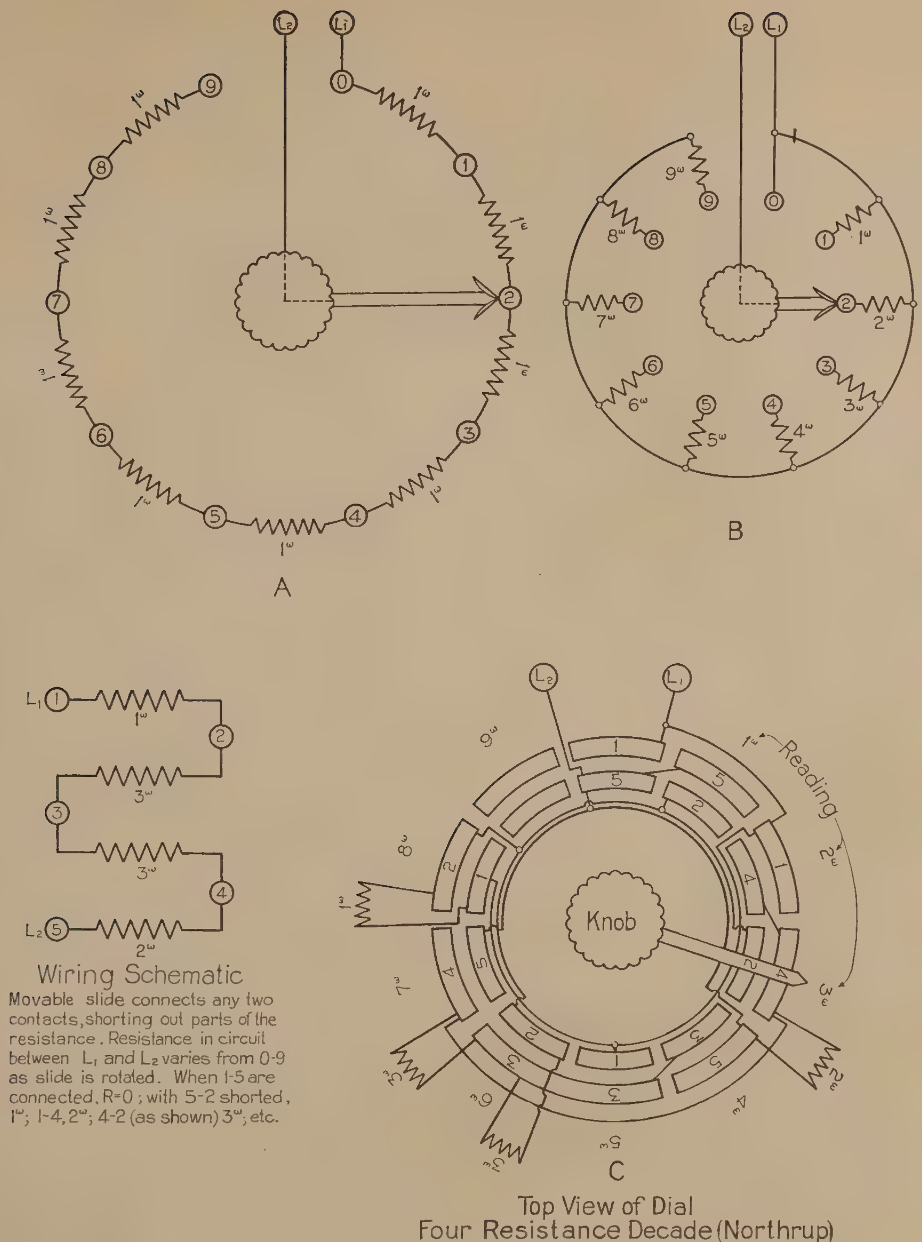
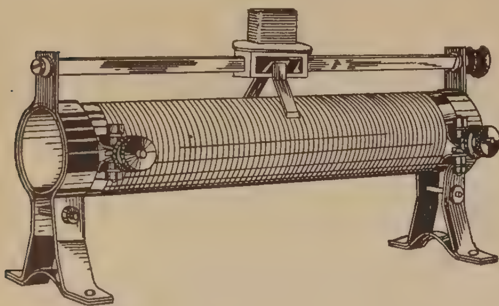



*Fig. 156—Wheatstone Bridge Dials.*

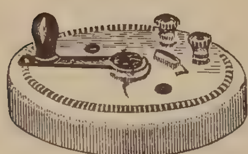
A type of relay still standard for certain telephone circuit uses, though of older design than the "A", "B" or "E" types, is coded as the #122-type and is shown in Figure 165. Its mechanical appearance is similar to the #178-type and with the exception of the number of groups of springs it is similar to the #125 (3 groups), #149 (one group) and #162 (one group). It has a spool winding and a laminated iron core with the magnetic circuit completed through the return armature and the soft iron framework at each end of the core. Relays of this design ordinarily have round caps which are fastened by means of a nut as shown in the figure.

The relays thus far described are intended to operate only on direct current. There are a few other types that may be classified as alternating

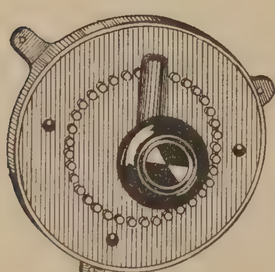
current relays, the more common of which are the "J" type, the #87-type, the #172-type, the #196-type, the #150-type and the #218-type.



Sliding Contact Tube Rheostat



Miniature Battery Rheostat



Motor Speed Rheostat

*Figure 157*

The "J" type relay is similar in appearance to the "B" type already discussed.

The #87-type which, while now obsolete, is still in use in many places, is designed to operate on 20-cycle ringing current, and to firmly close a set of contacts when so operated. It is illustrated by Figure 166. Its armature is made of a heavy block of soft iron pivoted near its center at an angle of about 30 degrees. When operated it becomes hori-

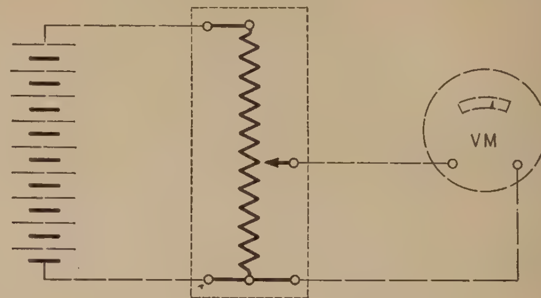



*Fig. 158—Theory of Potentiometer.*

zontal and is held so by the completed magnetic circuit through the core of the coil, the U-shaped framework and the armature itself. On account of its inertia, and on account of being pivoted so that it is nearly balanced, it is held in position by a pulsating magnetic pull, such as is given by the 20-cycle alternating current. The contact springs are specially designed to hold a firm contact in spite of the slight "quiver" of the armature that results from the alternating current operation.

The #172 and the #196 relays are not illustrated, but these more nearly resemble direct current types. The #172 is a toll line ringdown relay and the #196 is used for operating the toll line supervisory lamp of the toll cord circuit and in telephone repeater circuits designed for 20-cycle signalling.

The #150 and #218-type relays operate on 135-cycle alternating current and have a magnetic circuit similar to that of the polarized ringer. The #150-type relay is shown in Figure 167. The large permanent bar magnet establishes a split magnetic circuit through the cores of the two windings. The accurately adjusted reed between these two cores forms a return for the magnetic circuit. Just as alternating current in the winding of the relay will establish a vibration if it is in tune with the natural period of vibration of the reed, so when the reed is vibrating, the momentum of a contact spring with a weight on one end holds the contact open, except for an instant when the reed imparts a light blow to the spring. Ordinarily the winding of a second relay is in series with these contacts, and is operated by the contacts being open during the major part of the reed's period of vibration. The #150-type relay is used in composite ringer circuits and in connection with telephone repeaters designed for 135-cycle signalling. The #218-type is similar in construction and in use but is somewhat more sensitive. Also, it is equipped with a back contact so that the operation of the relay is positive, closing a contact.

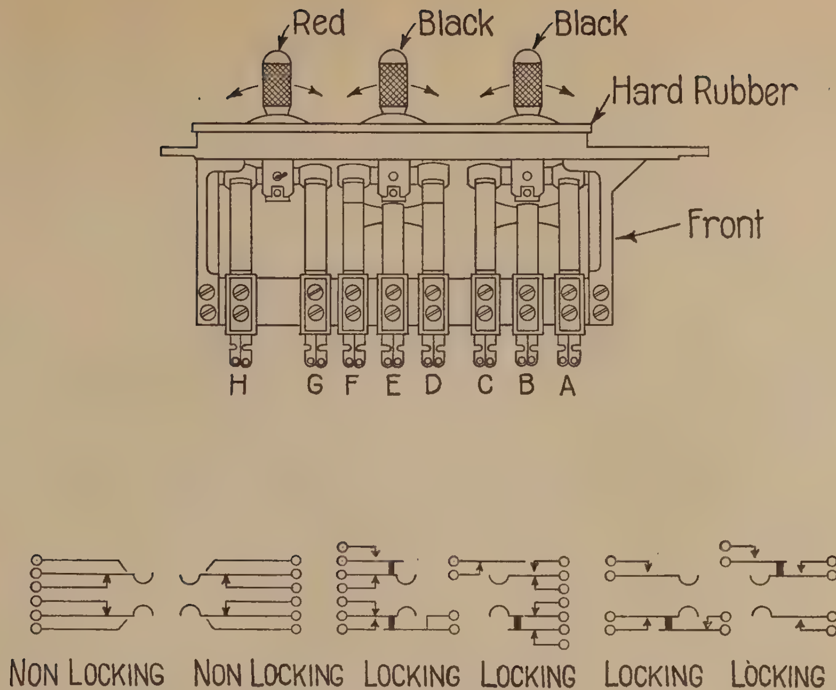



*Fig. 159—No. 463-C Key.*

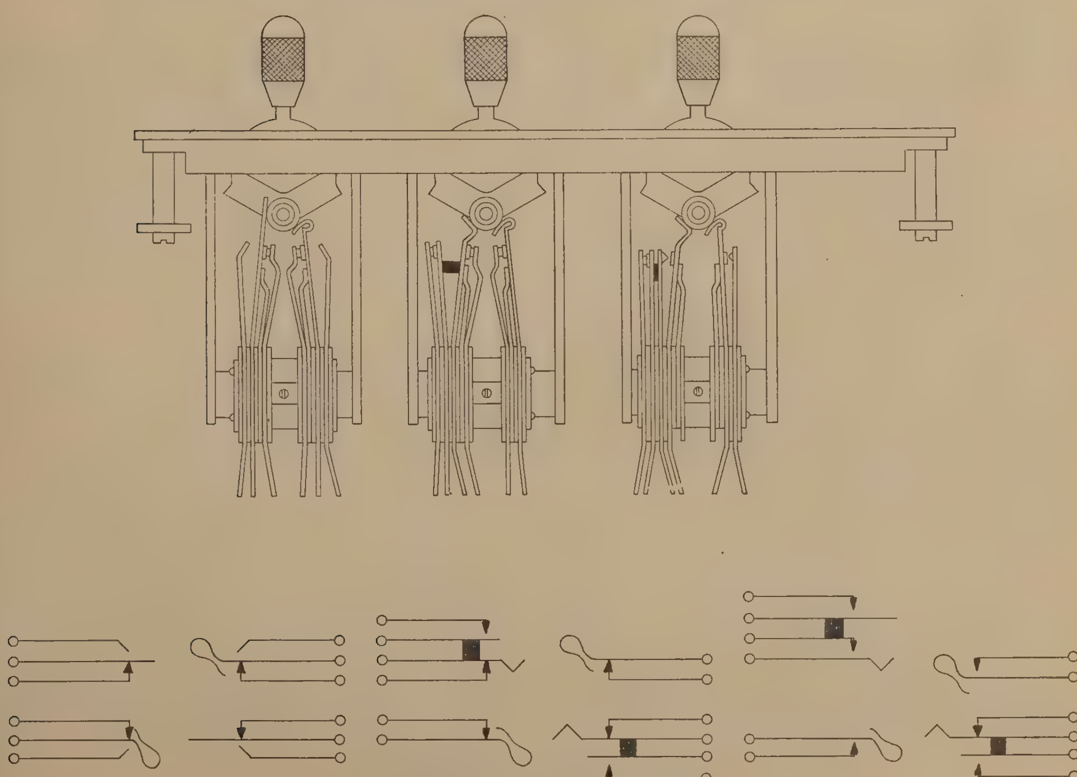


*Fig. 160—A1A-Type Key.*

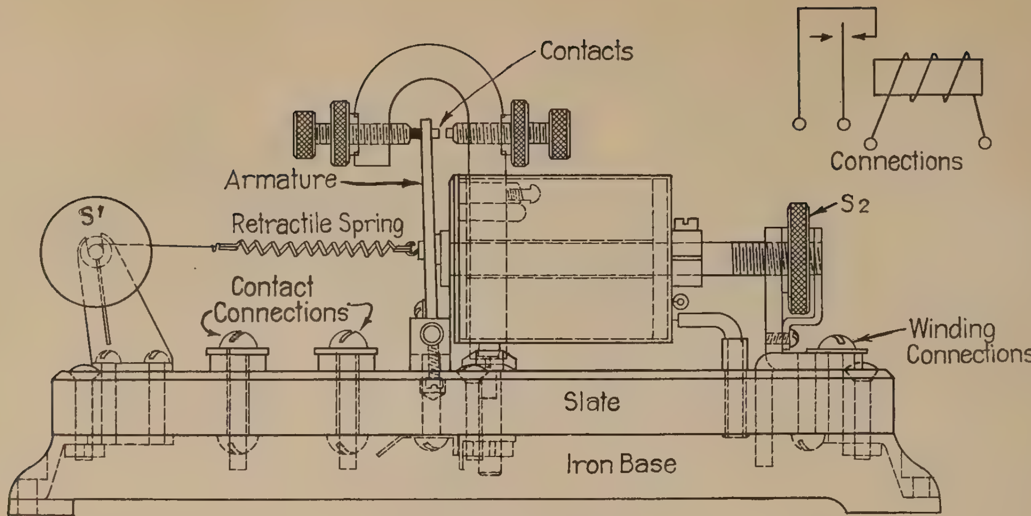



*Fig. 161—21 Type Relay.*

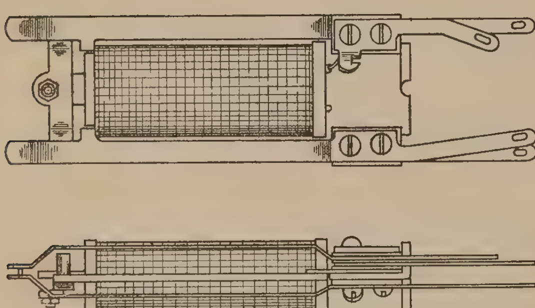


*Fig. 162—A-type Relay.*

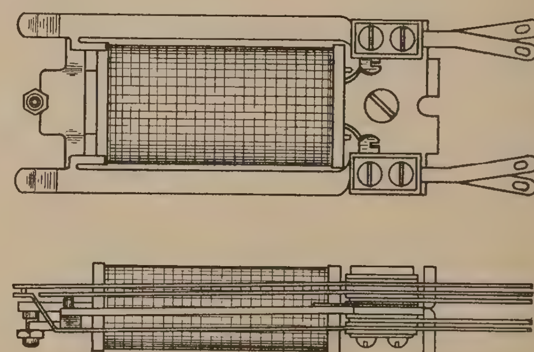


*Fig. 164—E-type Relay.*

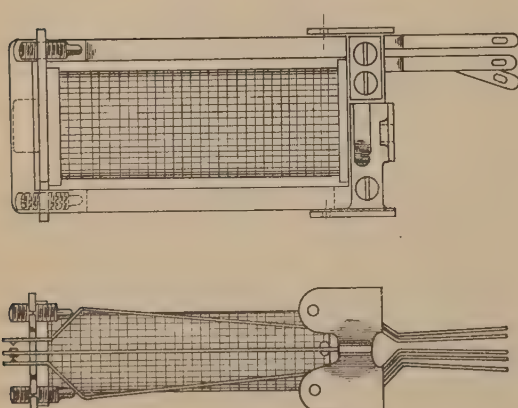


*Fig. 163—B-type Relay.*

**83. Operation of Toll Central Office Circuits in Establishing a Long Distance Connection—No. 1 Switchboard.**

We may now observe how various apparatus units are connected together and made to perform specific functions by following through, as an example, the operation of the circuits used in establishing a typical long distance connection over an open wire toll circuit terminated in No. 1 type switchboards. Figure 168 shows these circuits, the several distinct circuit units being grouped in blocks separated from one another by the cross-hatched lines.

To examine the operation of these circuits let us assume that a long distance connection is to be established using the standard single ticket method of operating. We may begin the analysis by considering that an outward line operator in the city

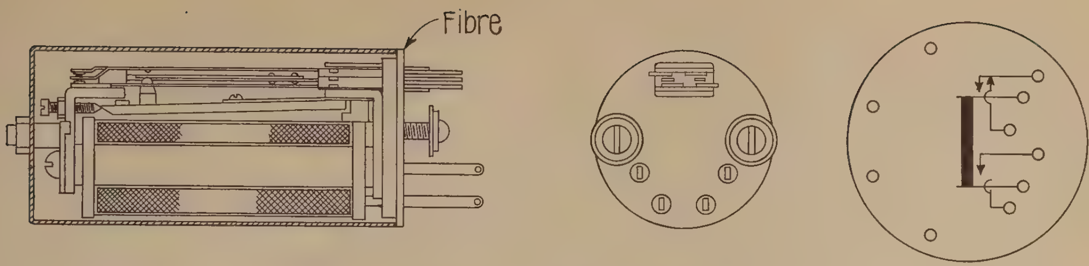



*Fig. 165—122 Type Relay.*

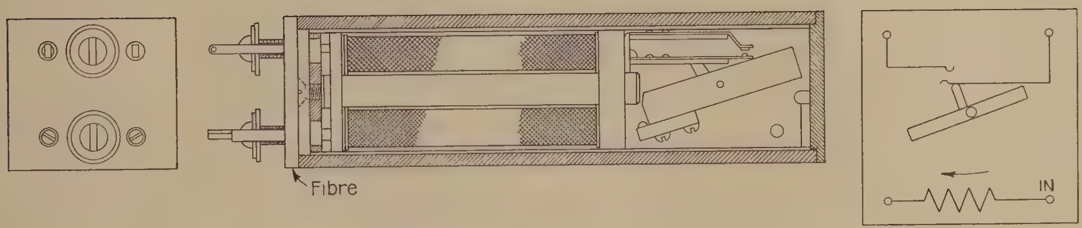



*Fig. 166—87 Type Relay.*

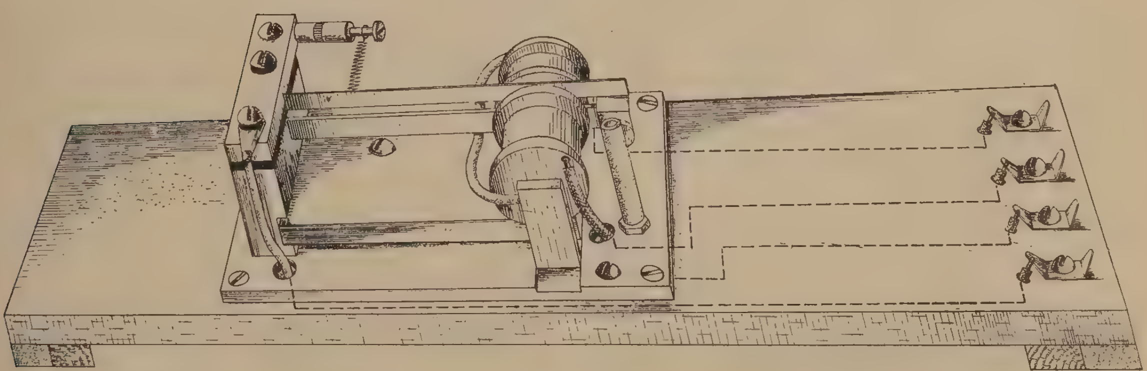


*Fig. 167—150 Type Relay.*

where the calling subscriber is located has received the toll ticket and is ready to begin work on building up the desired connection. Her first operation will be to connect the proper plug of a toll cord circuit to the outward jack of the toll line circuit. When this is done, a current will flow from the 24-volt battery connection through the 113 ohm winding of the E-156 relay of the cord circuit, through the sleeve of the cord itself to the sleeve connection of the toll line circuit multiple, through the 60 ohm winding of the E-702 relay of the toll line circuit, to ground, thus operating the E-702 and the E-156 relays. When the E-702 relay is operated one of the two springs connected to its armature breaks a contact which normally bridges a 172-B relay across the toll line, and the other makes a contact with a 24-volt battery connection that operates all the busy signals of the multiple, thereby notifying all other long distance operators that the particular toll line circuit is in use. The operation of the E-702 relay also disconnects the 24-volt battery from the winding of the E-28 relay for reasons to be given later. When the E-156 relay operated, it connected the 24-volt battery to the 162-B relay which operated it but did not light the supervisory lamp.

The long distance operator then rings over the toll line by depressing her ringing key, which is designated as key No. 3, in a direction which will operate the set of springs designated as F. These springs disconnect the toll cord from the toll cord circuit proper and connect it to energized ringing leads of 20-cycle frequency, one side of which is grounded. (This 20-cycle ringing current, however, will not be transmitted to the distant end as such if the long distance circuit is used for telegraph as well as telephone service and equipped with a composite set as shown. The 20-cycle ringing cur-

rent being so nearly similar in its characteristics to the telegraph currents will interfere with telegraph operation and, in addition to this, be greatly weakened when passing through the composite set which is designed to separate telephone from telegraph currents. It is, therefore, necessary in the test and telegraph room to have special equipment installed that will convert the 20-cycle ringing current into a current of higher frequency which will flow through the composite set in the same way that the voice current does and which will, furthermore, not interfere with proper telegraph operation. This is accomplished by means of a "composite ringer set", which is inserted in the circuit. The composite ringer set at the distant end will, in turn, receive the higher frequency ringing current, or the 135-cycle ringing current, and convert it into a 20-cycle ringing current similar to that originally sent out by the long distance operator.)

Now, assuming that the long distance circuit at the distant end is terminated in a "toll line circuit" identical to that in which it is terminated at this end, the incoming 20-cycle ringing current will flow through the winding of the 172-B relay, which is bridged across the distant end of the circuit since no operator at the distant end has a plug in the multiple. This 172-B relay is designed for operating on 20-cycle alternating current and the ringing current will, while flowing, close its armature contact. This closes the winding of the E-28 relay to ground, thereby permitting current to flow from the 24-volt battery connected through the unoperated contact at the E-702 relay to its winding. The operation of the E-28 relay in turn, operates the E-280 relay through its 250 ohm winding. The E-280 relay closes two sets of contacts, one of which permits current to flow through its 700 ohm winding, thereby "locking" it, that is, this relay will remain operated even after the ringing signal ceases and the 172-B relay contacts are open and the E-28 contacts are open, because current will flow from the 24-volt battery connection at the non-operated contact of the E-702 relay through this contact of the E-280 relay and through its own 700 ohm winding. Thus its contact will remain made as long as this current flows and this current will flow as long as this contact is made, unless the E-702 relay is operated.

In addition to locking itself, the E-280 relay closes another contact which operates the busy signals of the toll line multiple thereby notifying all other of the long distance operators at the distant end not to use the line because the operator at this (the near) end is using it to call an inward operator at the distant end. It also closes a third connection at its locking winding contact, through a non-operated contact of the E-651 relay, through a night transfer key to a line lamp at some one of the inward positions and through an auxiliary lamp relay to ground, thus lighting the line lamp. Two inward positions are ordinarily equipped with line lamp sockets, and in this drawing two line lamps are shown. This need not be confusing, however, as the second lamp socket is provided merely to give flexibility in the operating loads of the inward operators without making any cross-connections or other complicated changes.

The inward operator at the distant end then answers this lamp by inserting the toll plug of her toll cord circuit in the inward jack and connecting her head set to this cord circuit by throwing key No. 1 so as to operate the springs designated as B which gives a direct bridging connection for her head set across the cord circuit, and also opens a set of auxiliary spring contacts that are provided for a special feature of the cord circuit to be discussed later. The operator has a standard operator's telephone circuit, which consists of a 528 receiver and a 234 transmitter. The receiver is connected through contacts of a non-operated E-106 relay to the terminals of a #65 induction coil designated 2 and T. The transmitter is connected to a 24-volt battery tap in series with a 12-AB retardation coil and the primary winding of the induction coil, which is in reality two windings in parallel. The 12-AB retardation coil tends to steady the transmitter current flow in the 24-volt battery, thereby reducing noise and compelling the fluctuations (which are in effect a superimposed alternating current) to flow through the 21-E bridged condenser in series with the primary of the induction coil instead of through the 24-volt battery. This tends to give the effect of a lower voltage battery, which is preferable for the operator's transmitter in that it prevents both loud clicks and other disagreeable loudness being heard in the receiver as side tone.

The talking current is induced from the primary of the 65-induction coil to the secondary winding, and in order that its full strength will not be heard in the receiver as side tone this winding has resistance in series with one-half of the winding which, together with the winding, gives a resistance of 500 ohms. However, the induced current, although weakened to some extent by this resistance, will flow over the connections to L and 2, through a 2 mf. condenser, to the contacts of the cord circuit talking key designated as B.

The distant toll operator not only connects her head set to the cord used in answering, but upon plugging into the inward jack establishes a sleeve connection through the E-156 relay of the toll cord circuit to the sleeve of the inward jack (which is different from the sleeve of the multiple jack) through a contact of the E-651 relay, through the winding of the E-702 relay, thereby operating the E-702 relay. This operates the busy signals for all jacks of the multiple in the same way as explained in the foregoing for the near end of the circuit, and in addition, breaks the 24-volt connections to the E-28 relay and to the locking winding of the E-280 relay. This unlocks the E-280 relay and opens its second winding at the same time, which releases its control over the busy signals, now taken up by the E-702 relay, and also breaks the circuit through the

line lamp which is no longer necessary since the operator has answered the call and the lamp need not burn thereafter. The E-702 relay also disconnects the bridged 172-B relay which received the original signal in order that this relay shall not weaken the voice current by forming a shunt during the conversation.

We now have the outward long distance operator at the near end of the circuit in communication with the inward long distance operator at the distant end of the circuit, and assuming that the distant operator succeeds in getting the called party on the line, she will throw her talking key to normal after telling the called party that the distant operator (that is, the operator at this end) is calling. This leaves the procedure in connection with handling the call entirely up to the outward operator at this end, with the exception of pulling down the connection at the distant end when the conversation is finished, which is merely a matter of disconnecting the plugs when that operator finds the supervisory lamps associated with her cord circuit burning.

The outward operator at this end now having the called party on the line presses a call circuit key (indicated but not shown on the drawing) which will connect her head set directly to the B-board operator at the local central office. Upon giving the B-board operator the number of the subscriber who placed the call and receiving from the B-board operator the number of the "toll switching trunk" which is to be used for the connection, the long distance operator will plug the other end of her toll cord circuit into the toll switching trunk multiple of trunk No. 10, for example, and upon so doing will close a sleeve circuit to ground through a 500 ohm resistance connected to the toll switching trunk multiple sleeve. This will operate the B-261 relay in series with the E-1466 relay and the 12 ohm winding of the E-156 but will not operate the E-1466 relay on account of the current being too weak. The E-24 relay is next closed and its armature closes the talking connection from the cord circuit keys to the talking conductors of the plug and disconnects a busy test feature of the operator's telephone set circuit.

This busy test feature would have given the toll operator a "click" in her receiver if she had attempted to plug into a busy toll switching trunk instead of the one assigned her by the B-board operator. This click would have been caused by the operation of the B-86 relay which permits a rush of current from the 24-volt battery through one winding of the 20-G repeating coil to ground. This repeating coil is associated with the 65-induction coil. But assuming that the operator plugs into the proper trunk, if the line of the subscriber who has placed the long distance call is not busy, the local B-board operator will connect the plug of the incoming trunk circuit to that line in the B-board multiple. If the line is busy, upon attempting to make this connection, the B operator will get a click in her receiver by a busy test feature associated with the trunk similar to that connected to the toll cord circuit, and instead of plugging the trunk into the subscriber's line she will plug it into one of a special group of jacks which are connected with an interrupter that sends back to the toll operator over the trunk a signal known as the "busy back".

But assuming the line is not busy and that the connection is made, the E-122 relay of the trunk circuit will be operated by closing a 24-volt battery circuit through its winding, through the sleeve of the B-board multiple, through the cut-off relay (A-26) of the subscriber's line circuit to ground. The operation of the E-122 relay in addition to disconnecting the "B" operator's busy test will, through other contacts, connect a guard and disconnect lamp associated with the cord of the incoming trunk to the contact of the 124-F relay and disconnect it from the contact of the B-15 relay and the 30 ohm winding of the E-126 relay. If the B-board operator finishes her connection to the subscriber's line before the outward long distance operator finishes her connection with the trunk, this signal will burn, but as soon as the outward long distance operator finishes her connection, this signal will go out. This assures the B-board operator that the long distance operator has understood the trunk number assigned and has plugged into this particular trunk.

The reason this guard and disconnect signal goes out is the operation of the 124-F relay, which breaks the lamp connection, and in turn, closes a connection to the 30 ohm winding of the E-126 relay but does not operate the E-126 relay on account of the other side of this winding being open. The 124-F relay is operated due to the toll operator's cord circuit forming a shunt and a current from the 24-volt battery tap flowing through a 500 ohm winding of this relay to the contact of the E-126 relay, through one winding of the 25-S repeating coil, over one conductor of the trunk to the long distance office, over one conductor of the toll cord circuit to the bridged connection of a 44-D retardation coil (between the splitting and ringing keys), through the windings of the 44-D retardation coil, through the contact of the E-1466 relay, and through the winding of the B-43 relay to the other side of the cord circuit and back over the trunk to the other 500 ohm winding of the 124-F relay, thus operating it. (The resistance shown in series with the 500 ohm windings of the 124-F relay and designated as "X" is adjusted in value to compensate for different lengths of trunk circuits.)

We now have the connection established, the 124-F relay operated, and the lamp not burning at the B operator's position, telling her that the trunk is in use, needs no attention and must not be disconnected. The same current that operated the 124-F relay of the trunk circuit in flowing through the B-43 relay of the toll cord circuit operated it as well and lighted the trunk and toll line supervisory signal of the toll cord circuit, thereby signifying to the operator that she must ring the subscriber. She rings the subscriber by depressing her ringing key

in such direction as to operate the springs designated by E which send 20-cycle ringing current over the toll switching trunk to the local office. This causes the 87-A relay, during the interval that the ringing current is flowing, to connect a ground to the E-122 relay which, in turn, sends ringing current to the subscriber's telephone. Incidentally this ringing current flows through contacts of a special key so wired that it can be set to reverse the ringing connection and permit "party line ringing" from the toll cord circuit. This key is set at the same time the trunk is plugged into the B-board multiple, in case the long distance operator passes a number to the B-board operator having a "J" or "W" associated with it.

We thus have the ringing current properly relayed at the local office and when the subscriber answers, a 48-volt battery current will flow through the winding of the B-15 relay, through the 40 ohm non-inductive resistance and one winding of the 25-S repeating coil, over the subscriber's line and back to ground, through the other winding of the 25-S repeating coil and a second 40 ohm non-inductive resistance. This 48-volt circuit is, of course, the subscriber's battery supply and is used in connection with toll switching trunks to improve the subscriber's transmission over long subscribers' loops. The 40 ohm resistance in series with the repeating coil prevents, however, the current being too great on very short loops. Neither this resistance nor the winding of the B-15 relay can appreciably weaken the voice current on account of a condenser being bridged between the terminals 3 and 8 of the 25-S repeating coil; likewise, the winding of the 87-A relay between terminals 1 and 6 does not weaken the voice current on account of the bridged condenser between 1 and 6 of the other side of the repeating coil.

When the B-15 relay operates, due to the subscriber taking his receiver off the hook, its armature contact closes the 200 ohm winding of the E-126 relay through a 600 ohm resistance, through the 30 ohm winding of the same relay to the ground connected to the armature of the 124-F relay. This operates the E-126 relay which disconnects the 124-F relay from the bridge of the long distance operator's cord, but connects one winding of it to ground, which will hold it operated and keep the disconnect signal from burning. This interrupted flow of current through the toll cord circuit bridge releases the B-43 relay of the toll cord circuit, putting out the trunk and toll line supervisory signal, thereby notifying the long distance operator to cease ringing since the subscriber has answered. She then, having her talking key depressed, notifies the subscriber that she is "ready on his long distance call". After this she throws the key lever of her talking key in the other direction, which operates springs A instead of springs B and this disconnects her telephone circuit but connects the 27-F repeating coil and operates the E-106 relay. The E-106 relay switches the telephone receiver from the head set circuit to terminals 7 and 8 of the 27-F repeating coil circuit, thereby permitting the operator to listen, in such a manner as not to seriously affect the subscriber's transmission.

As soon as the subscriber starts talking, the operator stamps the ticket and sets key No. 1 normal, which disassociates her head set from the connection altogether, unless for some reason it is desirable to continue monitoring.

When the E-106 relay is operated it establishes contacts other than those for switching the telephone receiver from the head set circuit to the 27-F repeating coil. These additional contacts are associated with monitoring taps which connect the operator with the service observing board, thereby permitting the service observer to listen in on the circuit either when the operator is talking or monitoring.

When the subscriber has finished talking and hangs up the receiver on the hook the B-15 relay of the toll switching trunk circuit is released which, in turn, releases the E-126 relay, and this relay again connects the 124-F relay over the trunk to the bridge of the toll cord circuit and operates the B-43 relay which lights the trunk and toll line supervisory signal, thus notifying the long distance operator that the subscriber has hung up. After stamping the ticket she pulls down the connection with the toll switching trunk, releasing the 124-F relay and in doing so lights the guard and disconnect signal in front of the B operator. This time the B operator knows that the burning lamp means "disconnect" and pulls down the cord. This releases the E-122 relay which lets the guard and disconnect signal again go out, telling the B operator that the trunk is not in use and no further attention is needed. The long distance operator again rings the long distance inward operator at the distant end, but this time the signal does not display a lamp associated with the toll line circuit on account of the inward operator's toll cord circuit being connected. Instead, the signal is displayed by means of the ringing current operating the 196-A relay which is bridged across the cord circuit and which, in turn, releases the 162-B relay, permitting the toll line supervisory signal to light on account of the 24-volt connection through the contacts of the E-156 relay, the contact of the 162-B relay as well as the locking contacts of the 162-E relay and the auxiliary contacts of the talking key through the auxiliary signal relay indicated but not shown. This is a signal for the inward operator to clear the circuit and is additional to the signal she will receive when the distant party hangs up.

Both the toll line circuit and the toll cord circuit have features which were not explained in connection with this particular call. One feature of the toll line circuit is the night transfer key which permits grouping the inward signals. One night operator will handle as many incoming toll circuits as several inward operators handle during the day. Another feature is the use of non-locking keys associated with lamps at the inward position, which

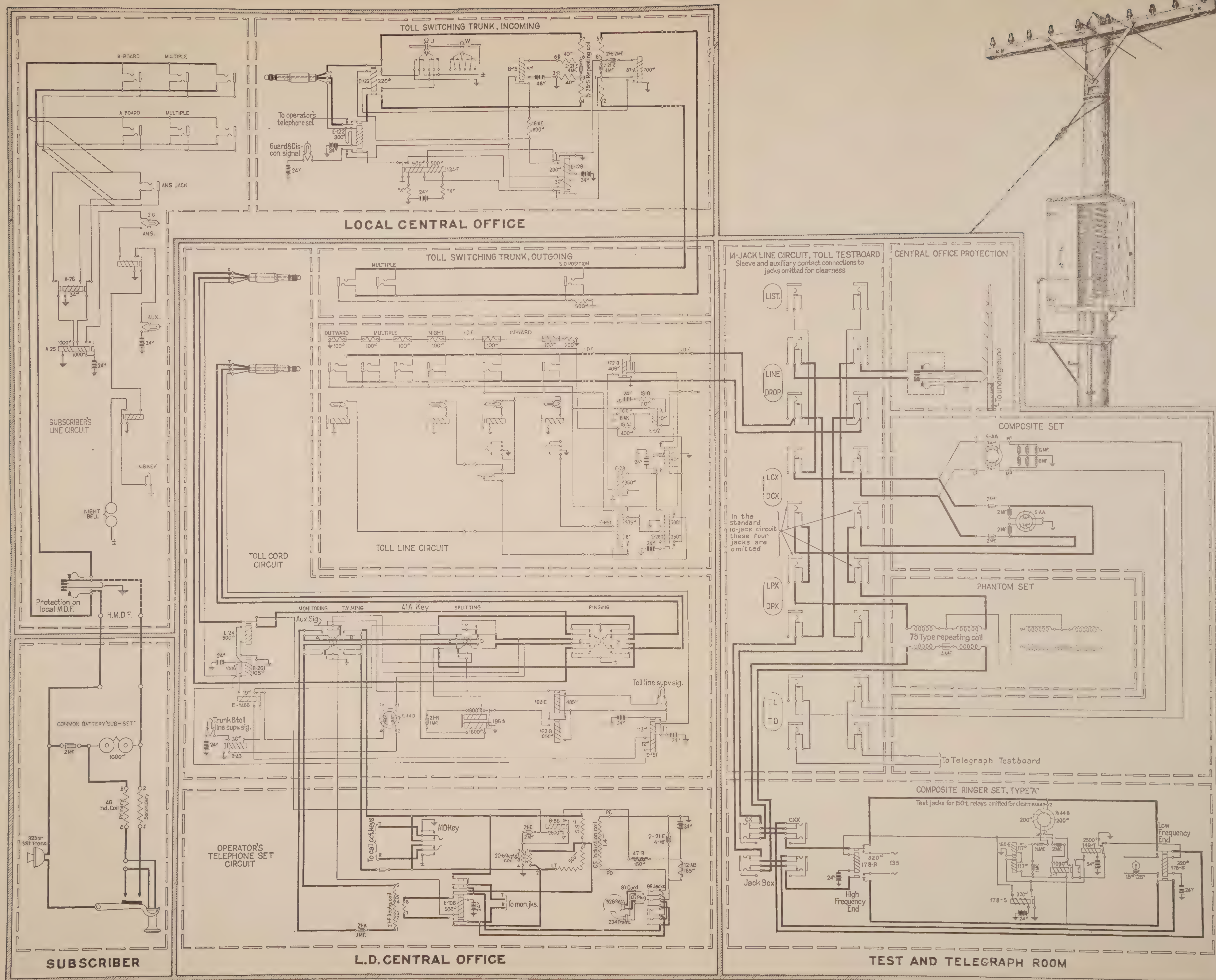



*Fig. 168—Typical Long Distance Terminating Connection. Open Wire Circuit—No. 1 Switchboard.*

when pressed by the inward operator will transfer a call from the distant office to an outward operator by extinguishing the inward line lamp and operating the E-651 relay which will burn the outward line lamp. This is for use where the method of operation is such as to require that tickets be made at both ends of the circuit or for delayed traffic where the distant office's outward operator will make all subsequent attempts to locate the called party.

A special feature of the toll cord circuit is the E-1466 relay which is "marginal" and operates on the current which flows when the plug is connected to another toll line circuit. The operation of this relay opens up the direct current supervisory bridge through the B-43 relay, eliminating its shunting effect upon transmission in case the toll cord circuit is used for a switching connection, that is, when two toll line circuits are connected together instead of one toll line circuit connected to a switching trunk. Another feature is the splitting key, which permits the operator to talk on one end of the circuit without the party at the other end hearing; thus she can communicate with the calling party or the called party at will. Auxiliary contacts of the splitting key have special relay connections whereby she will receive an incoming signal on the other end of her cord circuit in case the splitting key is thrown. A special feature of the operator's telephone circuit is a ringing key associated with the call circuit keys which permits ringing on call circuits at night or in other cases where the B-board operator "answers in" on call circuit signals instead of having a head set permanently connected to a group of call circuits.

We have mentioned the functions of the circuits shown associated with the long distance connection in the test and telegraph room and we may now direct our attention to their operation in detail. For the open wire terminating circuit illustrated in Figure 168 three distinct apparatus circuits are shown, namely, the composite set, phantom set and composite ringer set, which represent apparatus units installed on relay or coil racks and cabled in this case to a single group of fourteen jacks, designated as a "14-jack line circuit" in the toll testboard. In present installations a 10-jack line circuit is used instead of the 14-jack circuit but many 14-jack circuits remain in use and it is accordingly selected for our example. Figure 169 shows diagrammatically the order in which these circuits are connected with respect to the 14-jack line circuit and may be helpful in following the connections shown by Figure 168. In either figure if we trace carefully the long distance circuit from the long distance operating room to the underground cable, we shall find it first connected to the drop jacks in the testboard line circuit by means of cross-connections at an intermediate distributing frame. In order that the busy test feature may apply to the testboard circuit as well as the long distance switchboard multiple, a third conductor is used which connects to the 14-jack line circuit.

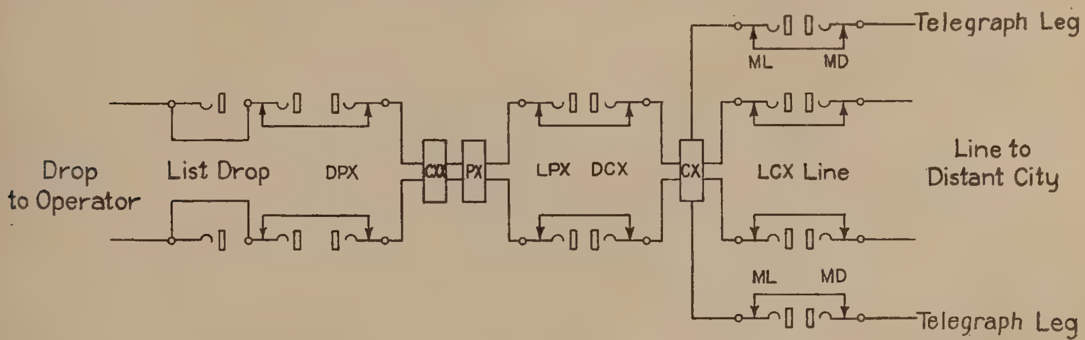



*Fig. 169—Line Circuit Jack Connections at Toll Test Board.*

This and all of the auxiliary contact wiring is omitted for the sake of clearness, and we may consider only the talking conductors that terminate on the tip springs of the two jacks designated as "drop". If the #241 plug of the testboard man's testing circuit is inserted in these jacks, the testing circuit will be connected with the toll switchboard, and all other equipment in the test room, as well as the line itself, will be disconnected on account of the tips of the plug operating the springs of these jacks and opening the contacts shown. When the plug of the testing cord circuit is not inserted, however, the toll circuit is merely looped through the drop jacks and thence to contacts of two similar jacks designated as DPX, an abbreviation for "drop side of phantom set". The plug inserted here will likewise open up the circuit but will pick it up in the other direction, "looking" toward the line through all of the associated equipment in the test room with the long distance office disconnected instead of "looking" toward the long distance office with the other direction disconnected.

Leaving the DPX jacks the circuit is looped through other jacks at a composite ringer jack box and is connected to the armature springs of a 178-S relay at the low frequency end of the composite ringer set. When this relay is not operated the

circuit continues but has bridged across it the composite ringer signalling apparatus and is connected to the outer contacts of the 178-R relay at the high frequency end of the composite ringer set. Continuing, it again loops through the composite ringer jack box and is carried by means of cable conductors to the drop winding of one coil of a phantom set. The line winding of this phantom set is connected to springs of two other jacks of the testboard circuit designated LPX, which is an abbreviation for "line side of phantom set". A plug inserted here will open the long distance circuit and pick up the central office end through the phantom coil and the composite ringer. With no plug inserted the circuit merely loops through these jacks and straps to contacts of other jacks designated as DCX, meaning "drop side of composite set". Leaving the springs of these jacks, the circuit is carried through the talking branch of the composite set, returning to the testboard and terminating on the springs of the LCX jacks or the "line side of the composite set" jacks. The DCX and LCX jacks permit the testboard man to pick up the circuit on either side of the composite set in the same manner that he can pick it up on either side of the repeating coil in tandem with the composite ringer. The contacts of the LCX jacks are strapped with the contacts of the line jacks and the circuit is carried from these through cable conductors to the horizontal side of the main distributing frame and by means of a cross-connection is connected to the protection associated with the underground cable conductors.

The operation of the composite ringer set is as follows: A 20-cycle ringing current from the long distance operator's ringing key reaches the bridged apparatus from the low frequency end of the circuit and flows through a 200 ohm winding of the 44-B retardation coil in series with a 2 mf. condenser and a J-1 relay. This operates the J-1 relay. Ground through the armature of the 149-T relay which is normally operated when the circuit is not receiving a signal from the distant end, is connected to both the winding of the 178-R relay at the high frequency end and the 178-S relay. The 178-R relay operates and switches the line side of the circuit from its drop connection to the ringing leads from a 135-cycle ringing generator. This 135-cycle high frequency current will pass through the composite set to the line side of the circuit.

The same composite ringer set not only "arrests" the 20-cycle ringing current and substitutes in its stead an outgoing 135-cycle current but reverses the operation on an incoming ring from the distant end. In this case the 135-cycle high frequency current flows through a second bridge consisting of one winding of the 44-B retardation coil in series with a one-half mf. condenser and the winding of the 150-E relay in parallel with a 1 mf. condenser. The operation of the 150-E opens a connection to ground, permitting the armature of the 149-T relay to fall back and this connects the winding of the 178-S relay at the low frequency end to ground, thereby operating it and connecting the drop of the toll circuit to 20-cycle ringing leads which operates the 172-B relay of the toll line circuit. There are special precautionary features of the composite ringer set which prevent temporary impulses that may for an instant open the 150-E relay. These hold the 149-T relay from giving false rings. Such impulses ordinarily come from condenser charges incidental to 20-cycle ringing or harmonics of the 20-cycle ringing current. The second armature of the J-1 relay shunts the winding of the 149-T relay when the ringer circuit is operating in the other direction. The armature of the 178-S relay likewise forms a shunt which is not as rapid in its action but makes a steadier contact.

### 84. Operation of Toll Central Office Circuits in Establishing a Long Distance Connection—No. 3 Switchboard.

As a further example, Figure 168-A shows the circuits and apparatus provided to establish a connection to a four-wire cable circuit terminated in the more recently designed No. 3 switchboard. It may be interesting to compare the operation of this circuit with that which we have just been over. The principal point of difference between the No. 3 and No. 1 switchboards is that in the former all apparatus except one relay and the necessary keys is removed from the cord circuit proper and connected either in the toll line or outgoing switching trunk circuit or in a special circuit which may be used in common with any of the cords in a position, known as the operator's position circuit. This arrangement reduces quite materially the amount of apparatus mounted in the switchboard position and effects a large reduction in maintenance difficulties. There is also a change in the signalling circuits which, when it has been more completely adapted to existing plant, will introduce substantial economies.

Let us briefly follow through the operation of the circuits of Figure 168-A in the same way that we did those of Figure 168. When the outward operator connects one end of her cord to the toll line jack a connection is established from battery through the supervisory lamp of the cord circuit and the cord sleeve to the winding of the B-1019 relay in the toll line circuit. This relay operates but due to its relatively high resistance (1800 ohms) the current flowing is too weak to light the supervisory lamp. The operation of relay B-1019 is followed by that of the R-897 relay which operates the busy signals.

The operator now signals on the circuit by operating the ringing key in the proper direction which connects 24 volt battery in series with 28 ohms to the tip of the cord. This establishes a current through one winding of the 54-L retard coil and the winding of relay R-856 in the toll line circuit, which in operating connects 20 cycle ringing current to the outgoing line. This ringing current is converted to a higher frequency for transmission over

## TOLL OPERATING

*Above* — Through or "Rx" switchboard where switched connections between distant cities are established.

*Above*—Line switchboard where outgoing toll calls are handled.

*Left*—Close-up of line switchboard position. The operator is connecting one end of a cord circuit to a toll switching trunk, the other end being already connected to a toll circuit.

the toll line but is received at the distant switchboard as 20 cycles again, where it passes over the signalling bridge and operates the 196-A relay in the line signalling equipment circuit. This releases the normally operated 162-B relay connecting ground to the 300 ohm winding of the R-854 relay in the toll line circuit through a non-operated contact of the R897 relay. One armature of the former in closing operates the busy signals and through the other closed armature contact, the relay is locked up through its 475 ohm winding under control of the R-897, and battery is connected through non-operated contacts of the R-897 and R-855 relay to the signal lamps at the inward multiple.

The inward operator recognizes the signal by connecting one end of a cord to the jack which permits current to flow through the sleeve to the B-1019 relay operating it and in turn the R-897. The latter opens the battery connection to the line lamps and releases the locked up R-854. The operator answers on the connection by throwing her Talk key which through the resultant operation of the R-857 relay in the cord circuit and certain other relays in the operator's position circuit to be discussed later, connects her telephone set circuit across the line. The telephone set circuit differs in minor detail only from that described in connection with Figure 168.

When the other end of the cord circuit is connected to the switching trunk, a sleeve connection is closed through the B-199 relay in the outgoing end of the trunk, operating it. This closes a circuit through the winding of the B-1009 relay over the trunk and through the windings of the 124-F relay, operating both relays. The circuit of the incoming end of the trunk is identical with that of Figure 168 and functions in exactly the same manner. The operation of the B-1009 relay connects the 85 ohm winding of the B-199 relay in parallel with its 1800 ohm winding to the sleeve wire, the resultant reduction in series resistance permitting sufficient current to flow to light the cord circuit supervisory lamp. The toll operator then operates her ringing key which connects battery to the tip wire and so operates the E-65 relay in the trunk. This connects 20 cycle ringing current to the trunk which causes the operation of the 87-A relay followed by that of the E-122 which connects ringing current to the subscriber's line. When the subscriber answers, the B-15 and E-126 relays are operated in that order, the latter opening the circuit through the winding of relay B-1009 putting out the signal lamp.

Upon completion of the call, the outward operator rings on the toll line. The incoming signal at the distant end operates the 196-A relay in the line signalling circuit which releases the 162-B, grounding the lead to the toll line circuit. Due to the cord being connected to the circuit, however, the R-897 relay is now operated so that the grounded lead is now connected through its operated contacts to the winding of the B-1020 relay thence through contacts of relay E-6485 to the sleeve. The low resistance B-1020 relay now connected in parallel with the B-1019 reduces the sleeve wire series resistance to about 80 ohms permitting the cord circuit supervisory lamp to flash. The operation of relay B-1020 connects battery to one end of the winding of relay E-6193, the other end of which is connected to interrupted ground. This relay then operates intermittently causing a similar operation of relay E-6485 which, in turn, intermittently opens the connection of relay B-1020 to the sleeve circuit. The B-1020 is held operated, however, by battery supplied through the operated contacts of the E-6485 to one end of its winding, the other end being grounded through a pair of its own operated contacts. The net result is to cause the cord cricuit signal lamp to flash intermittently, and this will continue even after ringing stops until the inward operator either pulls down the cord or answers in on the circuit.

The inward operator may answer by throwing the talking key in her cord which disconnects the sleeve wire from the lamp circuit and connects it to battery through the windings of the B-1022 and B-1023 relays in the operator's position circuit in series. The combined resistance of these two relays is about 600 ohms, a value sufficiently high to so reduce the current flowing in the sleeve wire that the B-1020 relay, which is marginal, is released. This breaks the connection to the E-6193 and E-6485 relays, stopping their action and also increases the sleeve resistance to 1800 ohms. The B-1022 relay in the operator's position circuit is also marginal and does not operate but the B-1023, and following it, the R-1084 are operated. The operation of the talking key also establishes a circuit through a non-operated contact of the 149-BL relay in the position circuit and the 175 ohm winding of the R-857 relay in the cord circuit operating it. This breaks the direct connection between the two ends of the cord and connects them to the splitting key from which they are connected to the telephone set circuit through closed contacts of the two R-1084 relays which are both operated if both ends of the cord are connected to jacks.

The operator's position circuit is, as its name implies, common to all the cord circuits at a position. This means that each wire shown in Figure 168A as connecting from this circuit to the cord circuit is also connected in the same way to every other cord circuit in the position. It may be noted that with the monitoring and talking keys of the cord normal, every one of these wires is open at one end or the other. When the position circuit is connected to a cord by operation of the talking key, the cord may be split for talking in either direction by operation of the splitting key in the position circuit.

If, when the talking key is operated, a ringing signal is received over the line, it will operate the relays in the signalling circuit and connect ground through the operated contacts of the R-897 relay,

the winding of the B-1020, non-operated contacts of the E-6485 and thence over the sleeve wire and through contacts of the talking key and the windings of the B-1022 and B-1023 relays to battery. The current set up will not be great enough to operate the B-1020 relay but due to the connection of the B-1020 in parallel with the B-1019 in the sleeve circuit, the current will be of sufficient value to operate the marginal B-1022 relay in the position circuit. Its operation will reduce the resistance of the circuit of the cord circuit supervisory lamp, which may be traced through contacts of the talking key, from 1800 ohms to 80 ohms by connecting an 85 ohm resistance in parallel with the 1800 ohm resistance already connected to the lamp and grounded through a closed contact of the R-1084 relay, and permit the lamp to light.

Similarly a switch-hook signal from the subscriber, when the talking key is operated, will operate the B-1009 relay in the trunk circuit which will connect the low resistance winding of the B-199 relay into the sleeve reducing its net resistance and so allowing the B-1022 relay associated with that end of the cord to operate and light the other signal lamp.

The position circuit is so designed that if the talking keys of two cords are operated, only the cord whose key was thrown first will be connected to it. This is effected by means of the 149-BL relay which when it operates following the operation of the R-857 relay in the cord circuit whose key is thrown first, opens the ground connection to the 175 ohm winding of the R-857 and replaces it with a ground connection through another pair of contacts in the talking key and auxiliary contacts of the R-857 to its own 700 ohm winding. This holds the R-857 relay in the first cord operated but makes it impossible for the R-857 in any other cord to operate even though its talking key is operated because both windings will be opened, one by its own non-operated contacts and the other by the operated armature of the 149-BL.

It is possible, on the other hand, to monitor on two or more cords at the same time by operating the monitoring keys. It is possible also to talk and listen on two cords simultaneously by operating the talking key of one and the monitoring key of the other. In this case only the cord whose talking key is thrown is connected through the position circuit for splitting or transferring but the operation of the R-506 relay connects the monitoring leads from the second cord to the leads running to the telephone set circuit through two 2 mf. condensers.

The position circuit of Figure 168-A is arranged for transferring an incoming call from the inward to an outward position. The circuit may also be arranged for transferring from inward to through or, by adding another relay in the toll line circuit, for transferring from inward to through and outward. The transfer from inward to outward is accomplished by operating the transfer key shown in the circuit. This connects battery through 84 ohms to the ring wire of the cord permitting current to flow over this wire and through the 1-2 winding of the 54-L retard coil to the 165 ohm winding of the R-855 relay in the toll line circuit. Its operation opens the sleeve connection from the inward jack, thus releasing the B-1019 and R-897 relays. The simultaneous establishment of a ground connection to the 300 ohm winding of the R-854 relay, however, causes it to pull up and hold the busy signals operated. The closing of the R-854 and R-855 relays also establishes a connection from battery at the now opened contacts of the R-897 relay through a closed contact of the R-854 and the 7 ohm winding of the R-855 to the lamp signals at the outward positions. The R-854 and R-855 relays are locked up through their 475 ohm and 7 ohm windings respectively, so that the lamps at the outward positions remain lighted until the outward operator plugs into the jack even though the inward operator restores the transfer key to normal and pulls down her cord. When the outward operator answers, the operation of the B-1019 and R-897 relays due to the sleeve connection, breaks the battery connection to the signal lamps and the R-854 and R-855 relays, allowing them to return to their normal non-operated position.

From the switchboard, the line circuit is led through three pairs of jacks at the secondary testboard. There the circuit may be monitored by the testboard man and patches involving the drop circuit and the drop side of the four-wire terminating equipment can be made. An artificial line or pad is inserted between the HYL jacks at the secondary testboard and the four-wire terminating set, the primary purpose of which is to effectively lengthen the two-wire line circuit and so make possible a better balance between this line and the network associated with the terminating set. In cases where the equivalent of cord circuit repeater operation is desired a second pad having a 3 TU loss is also inserted at this point and is so arranged that it will be cut out when the circuit is connected at the through switchboard to another similarly arranged circuit, the net effect being to give the equivalent of a 6 TU repeater gain.

The four-wire terminating circuit is a device for breaking the circuit into two parts, a transmitting and a receiving circuit, each requiring a pair of wires. It consists of two 82-C repeating coils connected in the bridge transformer arrangement to be discussed in a later Chapter. A terminal composite ringer is bridged around the terminating set and the pad. This converts the 20 cycle signal coming from the drop to 135 or 1000 cycles for transmission over the toll line and likewise converts incoming high frequency ringing signals to 20 cycles for operating the signal receiving circuits at the switchboard. The two relays shown associated with the terminating set function in connection with the operation of the terminal ringer.

From the terminating set, the transmitting and receiving circuits pass through four jack circuits in

and out of the terminating amplifiers or repeaters, indicated by blocks in the drawing, and from thence to the line equipment. This consists of the composite sets, equalizing equipment and phantom sets which are connected directly together instead of being brought out separately through jacks at the testboard as in Figure 168. The composite sets shown in Figure 168A are arranged for metallic telegraph circuits and differ in detail but not in principle from those that have been previously examined. Equalizing apparatus consists of arrangements of resistances, inductances and capacities connected across the line on the line side of the phantom repeating coil in the transmitting circuit and in series with the drop windings of the repeating coil in the receiving circuit. The purpose of this is to broaden the band of frequencies through which transmission over the circuit will be practically uniform.

For line testing purposes and for patching the equipment, the line circuits are next connected through four-jack circuits at another testboard position called the primary testboard where a large number of cable pairs may be terminated conveniently since each pair occupies only a relatively small space in the testboard jack panels. From the line jacks here the circuits are connected to the distributing frame again and thence through protectors to the toll cable itself.

# CHAPTER XIV

## ALTERNATING CURRENTS

### 85. Source of Alternating E.M.F.

In taking up the study of that current flow hitherto classified as "alternating", we shall follow closely the same course as was followed in the study of direct currents. The theory shall preceed the applications, and step by step we shall pass from the simple circuit to the network, from the network to the transmission of electrical energy, and thence to our ultimate aim which is the application of these to the transmission of human speech. But along with this procedure we shall study wherein the distinctive nature of alternating current work differs from that of direct current work. Perhaps the first such difference lies in the source of E.M.F.

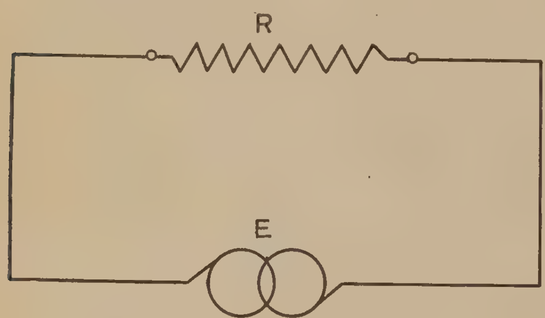



*Fig.170—Simplest A. C. Circuit.*

Figure 170 represents an alternating current circuit in its simplest form. In this figure we have a new convention for source of E.M.F. which represents the collector rings of a generator, and unlike the battery or other simple form of direct E.M.F., we cannot describe it by simply giving its voltage, for example, E = 10 volts. Here we have a voltage gradually increasing to a maximum value, and then decreasing to zero, to again increase to a maximum value in the opposite direction, and again decrease to zero where the cycle starts to repeat itself. Even if we knew the maximum voltage value we should not know the trend of the successive values from zero to the maximum value. Figure 171 illustrates cycles of alternating E.M.F.'s all very different in this respect.

Furthermore, we should not know the rapidity with which the alternations are taking place. For example, Figure 172 represents two cycles of identical E.M.F. values but in one case the cycle is completed in one-half the time required for the other. Therefore, **to describe electrically a source of alternating E.M.F. we must know the following:**

a. **The wave shape of the alternating cycle.**

b. **The value of the E.M.F. at some specified point on the cycle.**

c. **The length of time to complete the cycle, or the frequency.**

In classifying the conditions for the flow of current in a circuit in Chapter IX, we named two "steady state" conditions for alternating current; one, where the wave shape is the **"sine wave"** and

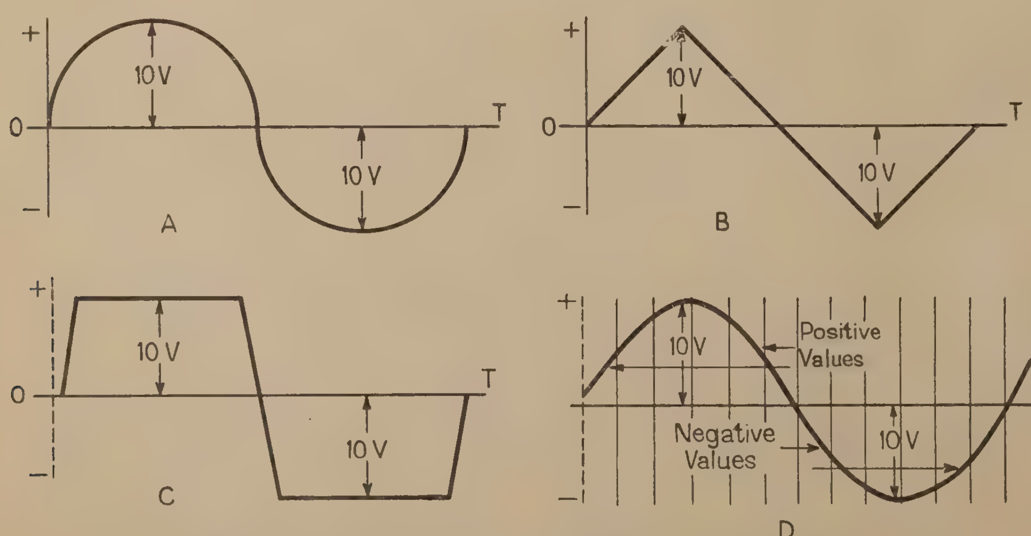



*Fig. 171—Theoretical Alternating Current Wave Shapes Compared with Sine Wave.*

the other where the wave shape is not a **sine wave** and is called a "complex wave". The basic study of alternating current circuits is founded on the sine wave for voltage and current shapes, and complex waves are analyzed into sine waves just as complex tones are analyzed into **"fundamentals"** and **"harmonics"**.*

## 86. The Sine Wave

The sine wave is named from a trigonometric function of an angle. We have learned how it may be constructed graphically and we may treat it as a "pattern" having a name with a mathematical origin to which an E.M.F. or current may or may not conform rather than as a mathematical expression requiring a thorough knowledge of trigonometry for interpretation. It has interesting properties and is the most natural wave form in all vibratory motion. It greatly simplifies alternating current circuits because—**A sine wave E.M.F. impressed upon a circuit having a network of any number and arrangement of resistances, inductances, and capacities with fixed values will set up a sine wave current in every branch of the network.** No other wave shape (excepting that of direct current) will give the same wave shape for the current as that for the impressed E.M.F.

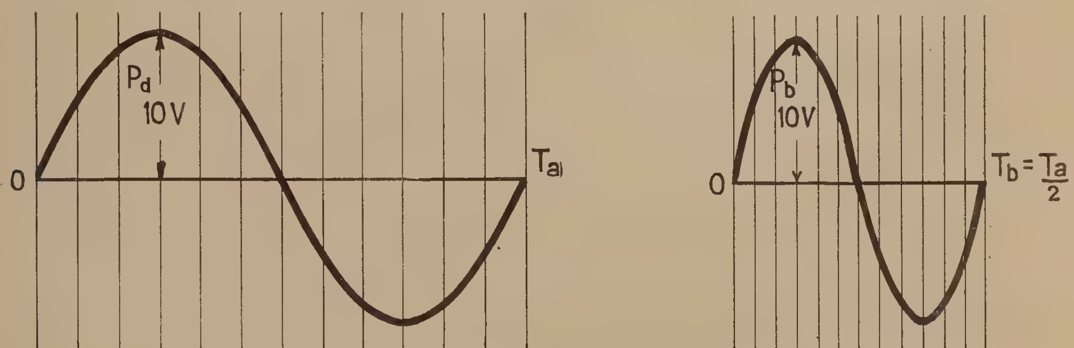



*Fig. 172—Comparison of Sine Waves of Different Frequencies.*

The above rule holds in all its applications since the sine wave possesses the following properties:

a. **Sine waves of the same frequency can be added (or subtracted) either in or out of "phase" and the wave shape of the result will be a sine wave.** ("Phase relations" will be defined later).

b. **A sine wave E.M.F. across a resistance, inductance or capacity gives a sine wave current through the resistance, inductance or capacity (though not necessarily in phase).**

c. **Whenever an E.M.F. is induced on account of the ever-changing value of a sine wave current, this induced E.M.F. is a sine wave (though not in phase).**

* See Appendix IV.

**Note:**—A graphical proof of property **a** may be had by referring to Figure 173. Here A shows a sine wave constructed graphically in the manner explained in connection with Figure 74. B is a similar sine wave of the same frequency but is constructed independently of A. Now if each value on the A curve, for example that represented by $P_a$, is added to each corresponding value on the B curve, for example that represented by $P_b$, the curve plotted will be that shown as C. But an inspection of C will show that it too is a sine wave and can be proven so by constructing a circle from values of the curve projected back. This is, of course, the converse of the construction of the sine wave and proof of the wave shape since there can be only one circumference drawn through the projected points of intersection with the radii of the circle.

The properties of a sine wave given under **b** and **c** in the foregoing can be demonstrated graphically by determining the rate of change or "slope" of a sine wave at various points and plotting the successive values of the slope as shown in Figure 174-B. When the value shown by the curve in Figure 174-A is zero as at point $Q_1$, the rate of change or slope is greatest. At any point between $Q_1$ and $R_1$, the slope is positive and is decreasing to its minimum value zero at point $R_1$. Between $R_1$ and $P_1$ the slope is negative and is increasing, attaining its maximum numerical value at $P_1$. After passing through $P_1$, the slope again decreases in magnitude, but is still negative, remaining so until point $S_1$ is reached. From $S_1$ to $T_1$ the slope again is positive, and increases in value until it attains its maximum numerical value at $T_1$. Curve B shows the curve that is obtained by plotting these values of slope. As before we can prove curve B a sine wave, if we wish, by projecting values back for the construction circle, but if the curve A and curve B are drawn with respect to the same axis, or we might say if curve B is superposed on curve A, we see offhand the striking similarity between

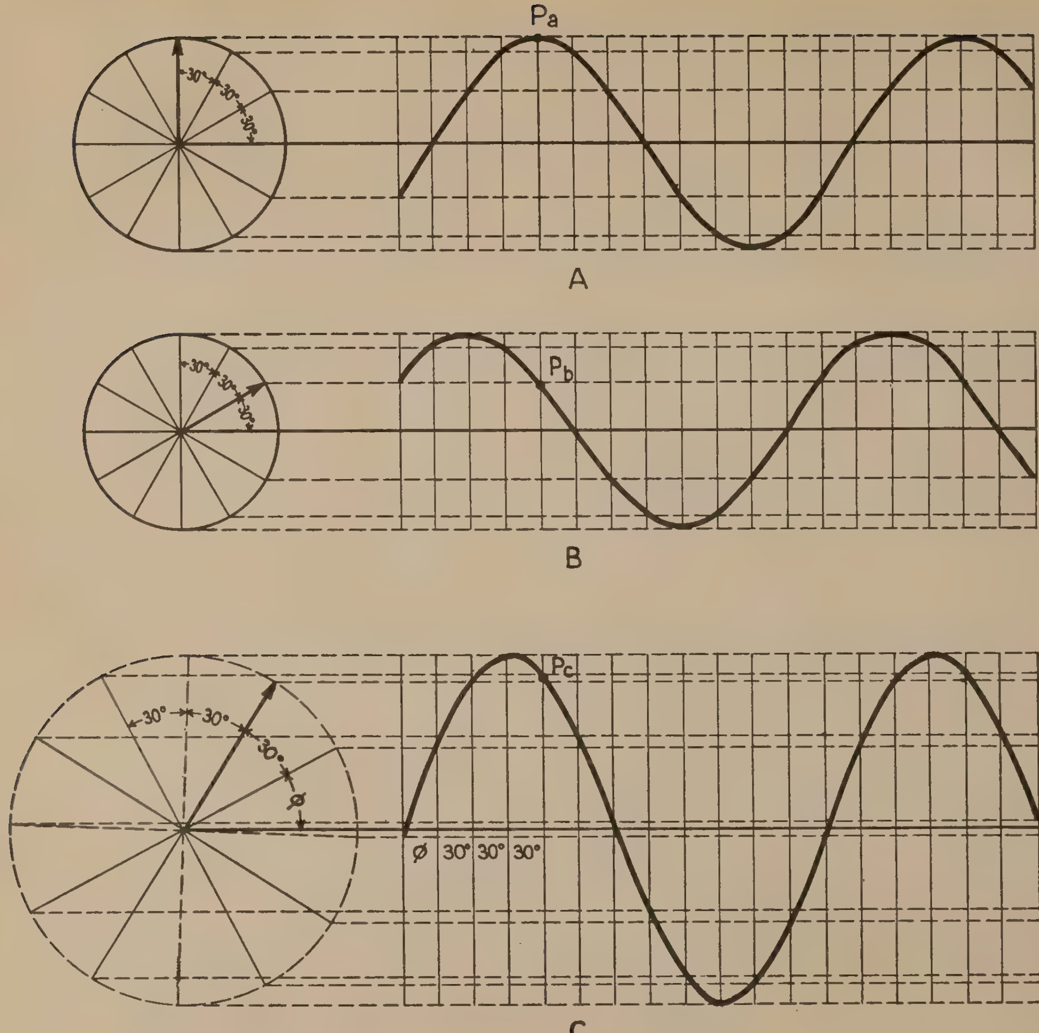



*Fig. 173—Graphical Proof That Two Sine Waves When Added Give a Sine Wave..*

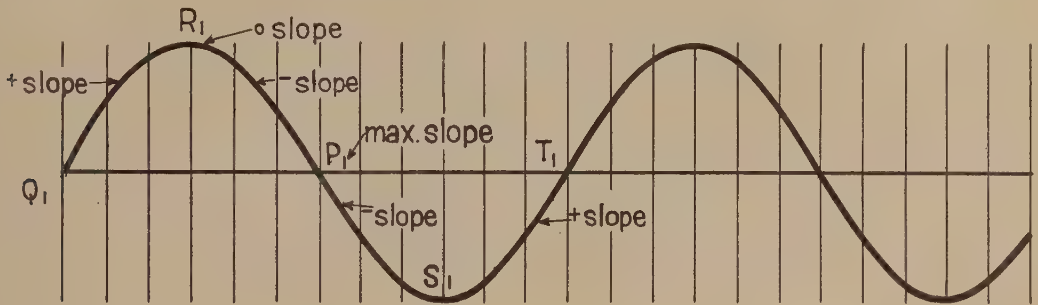
their wave shapes as is shown in Figure 174-C. (Though the curve B is a sine wave of the same frequency as the curve A, it does not follow that the maximum value of the curve B will always be smaller than that of curve A as shown in the figure. It may have a maximum value either smaller, the same, or greater depending upon the frequency value. To illustrate this more clearly, suppose we had charted the slopes of the two curves shown in Figure 172 which themselves have the same maximum values. The slope curve of the high frequency cycle (or short cycle) would have a maximum value twice that of the low frequency cycle because it is "twice as steep" at all corresponding points, such as the point where it crosses the axis (or at the zero value point.)

Granting, then, that the slope of a sine wave is another sine wave and that sine waves added in or out of phase give a sine wave for their sum, let us think of the connection between this and the properties stated in the foregoing with respect to the flow of alternating currents. First, since sine waves can be added in or out of phase it is obvious that currents in various network branches will combine at the branch junctions to give a sine wave. Second, we learned in Chapter IX that an induced E.M.F. (which in turn produces an "induced" current) depends upon rate of change of current or we can say slope of current wave. Let us assume a network of inductances with a sine wave E. M.F. impressed. In each individual inductance there is a sine wave **induced E.M.F.,** if a sine wave current. But there will be a sine wave

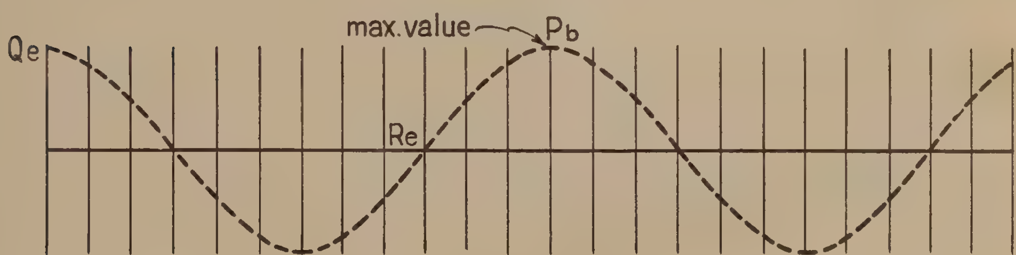
current because the induced current adds to or subtracts from the current that tends to flow due to the impressed E.M.F., and the sum or difference of two sine waves is a sine wave. Thus we can analyze all the current flow effects in the branches of any network by either an application of sine wave addition and subtraction, sine wave slopes, or a combination of the two properties.

### 87. Phase Relations and Vector Notation

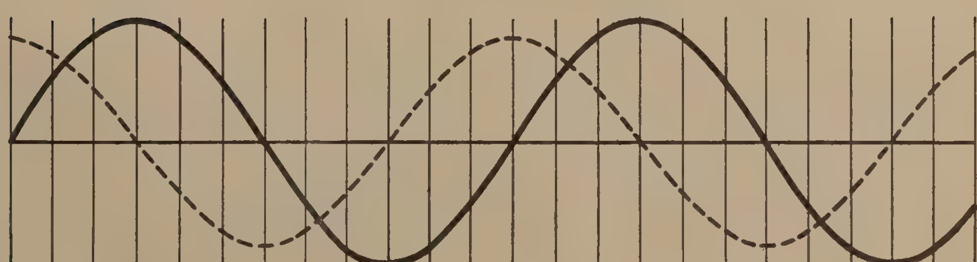
To illustrate what we mean by phase relation, we may well discuss a method of graphically representing alternating currents and alternating E.M.F.'s with "vectors". Figure 175 shows the graphical construction of a sine wave as described in Chapter VII. In this figure the horizontal scale (abscissae) represents time and the vertical scale (ordinates) represents instantaneous values of current. The complete curve, then, shows the values of the current for all instants during one complete cycle. It is convenient and customary to divide the time scale into units of "degrees" rather than seconds, considering one complete cycle as being completed always in 360 **degrees** or units of time (regardless of the actual time taken in seconds). The reason for this convention will be obvious from the method of constructing the sine curve as illustrated in Figure 175, where to plot the complete curve, we take points around the circumference of the circle through 360 **angular** degrees. It needs to be kept




A - Curve of Sine Wave




B - Curve of Sine Wave Slope



C - Curves A & B Compared.

*Fig. 174—Relation Between Current and Induced E. M. F.*

in mind that **in the sense now used, the degree is a measure of time in terms of the frequency, and not of an angle.**

Having adopted this convention, it is not necessary to draw the complete sine curve figure whenever we wish to represent the current in a circuit at a particular instant; for example, that current at the instant t, represented by the point P. If we know the frequency, the length and the position of

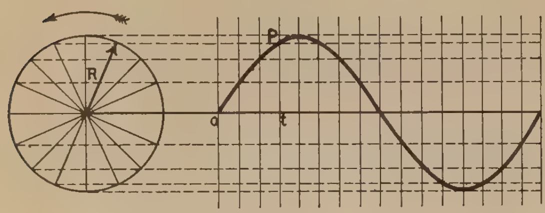



*Figure 175*

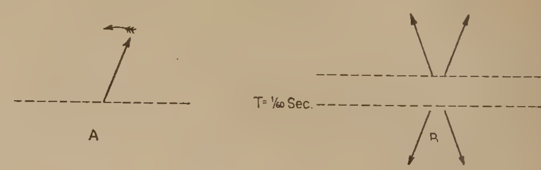



*Figure 176*

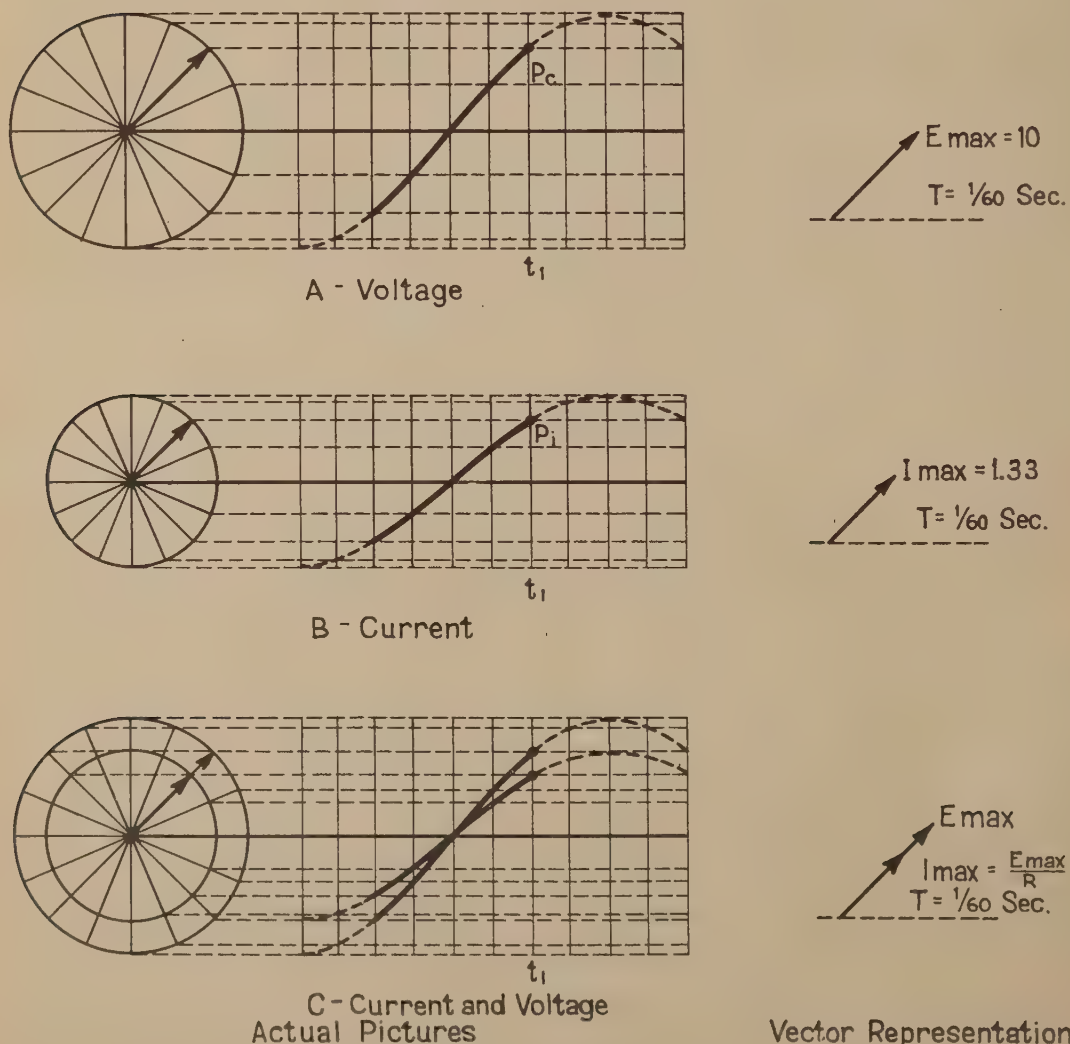



*Fig. 177—Current and Voltage in Phase.*

the single radius R corresponding to the point P, we have all the information we need to define the current. This is shown by Figure 176-A. Here we have what we call a **"vector" which we can imagine as a radius of the circle, having a length equal to the maximum current or E.M.F. value of the sine wave in question.** The angle this vector makes with the horizontal will give the position of point P and if we assume a direction of rotation for the vector, we can always determine by the position of the vector whether the value of the current or E.M.F. is increasing or decreasing and the direction in which the current flows. The accepted convention for direction of rotation is counter-clockwise and will be understood hereafter without the small arrow being used to indicate it. In Figure 170, let us assume the maximum value of E to be 10 volts, the frequency 60 cycles per second, and the value of R 7.5 ohms. Also let us assume the circuit to have negligible capacity and inductance. By arbitrarily adopting a scale, we can represent the E.M.F. at a given instant by Figure 177-A. Since the inductance and capacity of the circuit are negligible, the current at the corresponding instant will neither be retarded by inductance nor have a component part required to "charge" the circuit. It will be that determined solely by Ohm's Law. Consequently, it will change in value as the E.M.F. changes in value or will "keep in step", becoming a maximum of 1.33 amperes at exactly the same time that the E.M.F. becomes a maximum of 10 volts, and becoming zero at exactly the same time that the E.M.F. becomes zero. **The conventional expression to describe this relation between the voltage and the current is that the voltage and current are in "phase".**

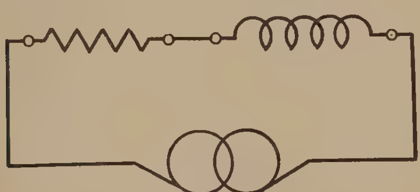


*Figure 178*

But if, instead of a circuit such as that shown by Figure 170, we have the circuit shown by Figure 178, it will be necessary to consider the effect of the inductance. This reacts to any change in current value, and an alternating current is changing in value at all times. We should expect, therefore, the inductance to materially affect the current in value and to throw the maximum points out of step, or phase, because the maximum value of current will not have been established until some time after the E.M.F. has reached its maximum value. Figure 179 represents the relation of voltage and current that are out of phase due to the circuit having inductance. Here the vectorial representation must **show the extent to which the voltage and current are out of phase and this is accomplished by having the voltage vector ahead of the current vector in its rotation by an angle which is a measure of the time by which the current "lags" behind the voltage and whose value is obvious from the relative position of the radii of the two circles.**

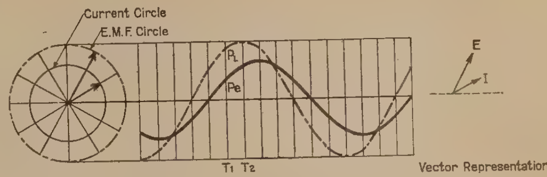



*Fig. 179—Current Lagging Behind Impressed E. M. F.*

In the case of a circuit having a series condenser instead of an inductance, the circuit reactions are the reverse and the current vector is ahead of or "leads" the E.M.F. vector as shown by Figure 180. Electrical conditions in circuits containing inductance or capacity, therefore, can be represented by current and voltage vectors, which will, in general, be out of phase. Moreover, in dealing with complex networks containing inductance or capacity, we encounter current vectors which are out of phase not only with their voltage vectors, but are out of phase with each other. In direct current networks, we used equations based on Kirchoff's Laws which called for adding or subtracting current or E.M.F. values. In alternating current work we cannot accomplish that by merely adding the numerical lengths of the vectors. We must **place the vectors end to end and draw a "resultant" line from the first to the last.**

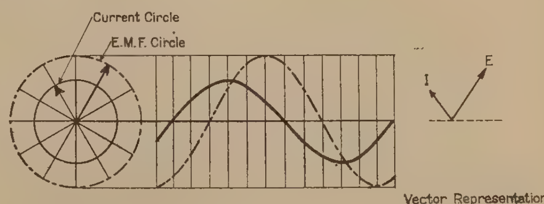



*Fig. 180—Current Leading Impressed E. M. F.*

**Example:** In Figure 181 the vectors shown opposite each branch of the circuit represent the respective currents in these branches at any instant. What current does the generator deliver?

**Solution:** Place the vector for branch 2 to the end of the vector for branch 1 and the vector for branch 3 to the end of the vector for branch 2. Draw the resultant as shown by Figure 181-A.

### 88. Effective E.M.F. and Current Values

In laying out current and voltage vectors thus far we have indicated in each case the current or voltage at some particular instant of time in its

cycle. The length of the vector gave the maximum value of the current or voltage and the angle that the vector made with the horizontal, in a counter-clockwise sense, indicated the particular instant being considered.

For practical purposes, however, it would be inconvenient to be always under the necessity of stating both a value and a position in time in defining an alternating current or voltage. It is advantageous, rather, to adopt some arbitrary standard so that only the value of the current or voltage need be given to define it, its position in time being understood from the convention adopted. The maximum value would perhaps appear to be the logical choice, but this has certain disadvantages. Another, and more useful value would be the average value over a complete half-cycle, this being equal for the sine wave to .636 times the maximum value.

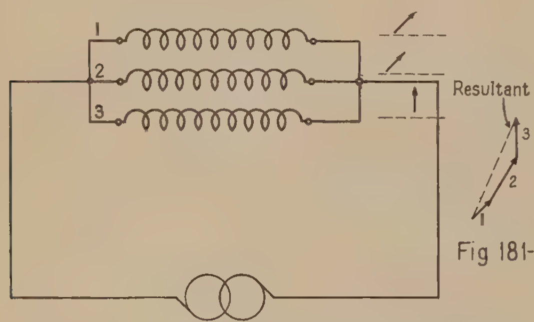



Fig 181-A

*Fig. 181—A. C. Circuit with Parallel Branches.*

Still more useful, however, is a value so selected that the heating effect of a given value of alternating current flowing through a resistance will be exactly the same as the heating effect of the same value of direct current flowing through the same resistance. The advantage of such a convention is apparent, since it obviates to a degree the necessity for thinking of the effects of alternating and direct currents as different. This value is known as the **effective** value and is equal to .707 times the maximum value, or—

$$I = .707\ I_{max.} \quad \ldots\ldots\ldots\ldots\ (42)$$

and $$E = .707\ E_{max.} \quad \ldots\ldots\ldots\ldots\ (43)$$

where E and I without subscripts indicate effective values. **Unless otherwise specifically stated values of alternating currents and voltages are always given in terms of their effective values.** Likewise, vectors representing currents and voltages give the effective value of the current or voltage by their length and, unlike the vectors we have previously considered, do not indicate by their angular position a particular instant of time within the cycle but only the time relationship of the current and voltage with reference to each other or to some other current or voltage in the same circuit.

## 89. Power in A. C. Circuits

Just as in D. C. circuits, the power in an A. C. circuit is **at any instant** equal to the product of the current and voltage in the circuit at that instant or we may write—

$$p = ei \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (44)$$

where the lower case letters mean that the values are instantaneous ones. The power in an A. C. circuit may, then, be shown by a curve each point of which is obtained by taking the product of the current and voltage at the same instant of time. Such a curve for the case where the current and voltage in a circuit are in phase is shown by Figure 182.

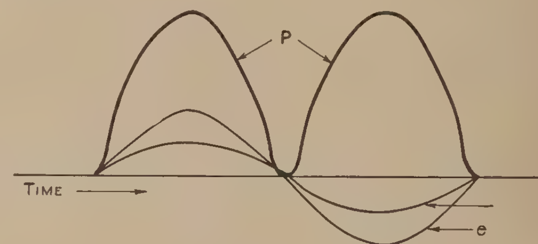



*Figure 182*

It will be noted that, since the current and voltage are both negative at the same time, the power loops are both positive which means that no power is being returned from the circuit to the generator. In other words, all of the power delivered by the generator is being absorbed in the resistance of the circuit. For this case, where, since the current and voltage are in phase, the circuit contains nothing but resistance, the average power is equal to the product of the effective current and voltage or we may write—

$$P = EI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (45)$$

and, as always, — $$P = I^2R \quad \ldots\ldots\ldots\ (46)$$

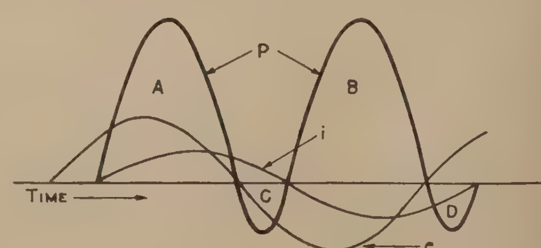



*Figure 183*

The condition where the circuit contains either inductance or capacity in addition to resistance, and the current and voltage are accordingly not in phase, is somewhat different. The power curve for such a case is shown by Figure 183. Here the product ei gives both positive and negative values and we have the positive power loops A and B and the

TABLE IX

| Conventional Symbols Used in Alternating Current Work | |
|---|---|
| Symbol | Stands For |
| P | Average power for a cycle of E. M. F. and current. |
| E | Effective E. M. F. for a complete cycle. |
| I | Effective current for a complete cycle. |
| $E_{ave}$ | Average E. M. F. for a complete cycle. |
| $I_{ave}$ | Average current for a complete cycle. |
| e | E. M. F. at some specific instant or instantaneous voltage. |
| i | Current at some specific instant or instantaneous current. |
| $E_I$ | Induced E. M. F. |
| T | Length of time in seconds (or fraction of one second) for a complete cycle. |
| f | Frequency which is the number of cycles per second, or one second divided by T. |
| Z | *Impedance in ohms. |
| $X_L$ | *Inductive reactance in ohms. |
| $X_c$ | *Capacity reactance in ohms. |
| X | *Total reactance in ohms. |
| Y | *Admittance in mhos. |
| $\Theta$ | Angle between current and impressed E. M. F., or between impedance and resistance, etc. |

*To be discussed in other articles that will follow.

negative loops C and D. The latter loops represent power returned to the generator from the circuit. The total power absorbed by the circuit is obviously equal to the sum of A and B minus the sum of C and D. In this case, then, the power, P, is no longer equal to EI but to something less than that. The factor by which EI must be reduced to obtain the true power is determined by the phase relation between the current and voltage, this power being—

$$P = EI \cos \Theta \quad \text{.................. (47)}$$

where $\Theta$ is the angle between the current and voltage. The term, $\cos \Theta$, is known as the **power factor** and has a maximum value of 1 when $\Theta$ is zero, or the current and voltage are in phase.

It may be noted that the expression, $P = I^2R$, remains true in this case and conforms with equation (47) because $R = Z \cos \Theta$ and $I = E/Z$, from whence

$$P = I^2R = I \times I \times R = I \times E/Z \times Z \cos \Theta = IE \cos \Theta$$

# CHAPTER XV

## ALTERNATING CURRENTS

(Continued)

### 90. Ohm's Law and Alternating Current Calculations

In Chapter I we learned that the relation between the voltage and the current in a D.C. circuit was expressed by Ohm's Law, or

$$\frac{\text{E (volts)}}{\text{I (amperes)}} = \text{R (ohms)}$$

We found this expression indispensable in our study of direct current circuits, and certainly we shall want to apply it to alternating current circuits if we are to make any calculations involving current and voltage values. On the other hand, we have learned of circuit properties other than resistance that influence alternating current flow. Moreover these properties, viz., capacity and inductance, not only change the value of the current in amperes but introduce changes in the phase relation of the current to the voltage. Again the effects of inductance and capacity depend entirely upon the particular frequency which we wish to consider. We must, therefore, introduce some new quantity that will express in ohms not only the resistance to current but the **combined effects** of resistance, capacity and inductance which will give the relation of E/I, at the same time remembering that it must be applied only to a definite stated frequency. This quantity is called **"impedance"** and Ohm's Law is adjusted to read

$$\text{Z (ohms)} = \frac{\text{E (volts)}}{\text{I (amperes)}} \quad \ldots\ldots \quad (48)$$

where Z is the symbol for **"impedance"** or **the combined effect of the circuit's resistance, inductance and capacity taken as a single property which can be expressed in ohms for any given sine wave frequency.**

It follows, then, that if we can by certain calculations reduce a circuit's resistance expressed in ohms, its inductance expressed in Henrys and its capacity expressed in microfarads to a single expression in ohms, we can calculate the current at a given frequency in any single branch as simply as though it were a branch of a direct current network. This requires that we consider the effects of inductance or capacity alone as coming from some characteristic of the circuit that produces a voltage drop acting in phase with and in place of the induced E.M.F. instead of in phase with the IR drop; in other words, that we consider the induced E.M.F. as a **voltage drop.**

This being done, we can concern ourselves with a somewhat simplified category of circuit properties. In addition to the impressed E.M.F. we have in the circuit only that physical property we call resistance and one other property known as **"reactance"** which can be expressed in ohms the same as resistance. However, in combining resistance and reactance into a single property measured in ohms, which we have already referred to as **"impedance"**, we must add them **"vectorially"** because they do not act in phase. We shall take up the calculation of **"impedance"** after first learning how the reactance may be determined for any **single frequency** from the inductance and capacity values in a given circuit branch.

### 91. Inductive Reactance

We have considered two factors as being involved in the calculation of the effects of inductance; first, the physical property of the circuit which we have called inductance and second, the rate of change of current value which uses inductance "as a tool" in creating the reactive effects. In an **alternating current circuit containing inductance, therefore, we should expect greater reactance for higher frequencies** because higher frequencies mean an increase in the "average rate of change" of current. By referring to Figure 184 this is apparent. Here are two current cycles of the same effective value but the "A" cycle has twice the period, or half the frequency of the "B" cycle. Also the slope of the "A" curve at any point such as $P_a$, is half the slope at any corresponding point such as $P_b$ on the "B" curve. The slope is, as has been seen, the measure of current change and we would expect, therefore, that the induced E.M.F. of the B curve would be twice as great as that of the A curve. Thus, the "reactance" due to inductance depends upon, first, the inductance of the circuit and second, the frequency of the current. As a matter of fact it can be proven that inductive reactance when expressed

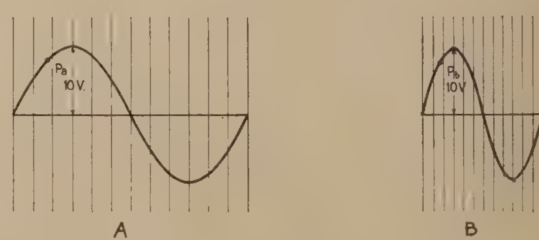



*Figure 184*

in ohms is equal to the **inductance in Henrys times the frequency in cycles per second multiplied by $2\pi$ or**

$$X_L = 2\pi fL \qquad (49)$$

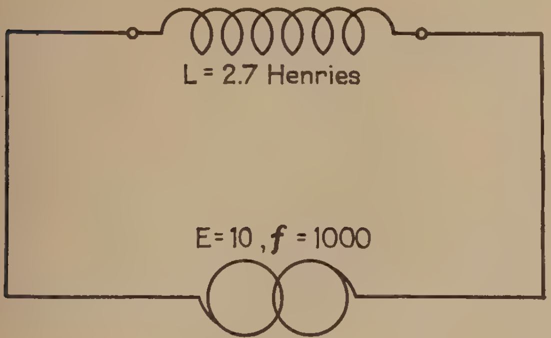



*Figure 185*

where $X_L$ is the inductive reactance in ohms, $\pi$ is the circumference of a circle divided by its diameter or 3.1416, f is the frequency expressed in cycles per second and L is the inductance in Henrys.

For practical use this becomes—

$$X_L = 6.2832\ fL \qquad (50)$$

**Example:** In Figure 185 assume that the source of alternating E.M.F. is a sine wave, 10 volts, 1000 cycles per second and the inductance shown has negligible resistance. What is the effective current through the inductance?

**Note:**—In practice inductance coils usually have appreciable resistance since any coil winding must have a definite length of wire; therefore, the condition assumed here is that the effect of the inductance is so much greater than that of the resistance that we may neglect the value of the resistance in the calculations.

**Solution:**

$$X_L = 6.2832\ fL = 6.2832 \times 1000 \times 2.7$$

$$= 16964 \text{ ohms}$$

$$I = \frac{E}{16964}$$

$$= \frac{10}{16964}$$

$$= .000059 \text{ amperes, ans.}$$

In this example, the current will be 90° behind the impressed voltage as shown in Figure 186, since the induced E.M.F. due to the current must be equal and opposite to the impressed E.M.F. and the induced E.M.F., as previously explained, is the rate of change or "slope" of current times the inductance and must, therefore, be 90° behind the current.

## 92. Capacity Reactance

Capacity reactance has distinctly opposite effects to inductive reactance—in fact the two tend to neutralize each other. Capacity reactance decreases with frequency and with the value of the capacity. It also tends to make the current lead instead of lag the voltage (see Figures 186 and 188), and if inductive reactance is assumed as positive, capacity reactance must be taken as negative.

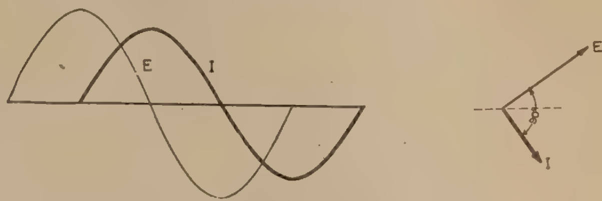



*Fig. 186—Effect of Inductive Reactance.*

**Note:**—The condenser action gives this current-to-voltage relation because with the equation $Q = EC$, a current must flow **out** of the condenser with a decreasing value of E and into the condenser with an increasing value of **E.** The "rate of transfer of quantity of electricity", or the current, is proportional to the rate of change of E and has a positive direction when there is an increasing E and a negative direction when there is a decreasing E. In other words the current of the condenser is in the opposite direction to the current that an induced E.M.F. would tend to make flow and must, therefore, be shown as a leading current with respect to the impressed E.M.F. instead of a lagging current. Also its maximum value would occur at the instant that the "slope of E.M.F." curve has maximum value making it lead by an angle of 90°

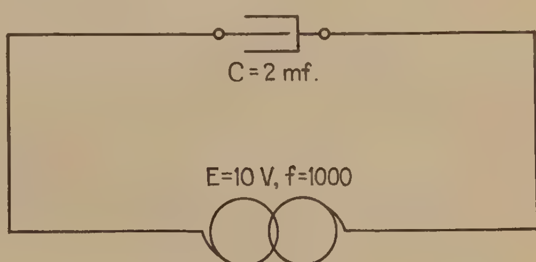



*Figure 187*

The equation for capacity reactance is as follows:

$$X_c = -\frac{1}{2\pi fC} \qquad (51)$$

where C is capacity in farads. Converting C to the customary capacity unit, microfarad, we have—

$$X_c = -\frac{1{,}000{,}000}{2\pi fC} \qquad (52)$$

or with 3.1416 substituted for $\pi$ —

$$X_c = -\frac{1,000,000}{6.2832\ fC} \qquad (53)$$

**Example:** In Figure 187, E is 10 volts, f is 1000 and C is 2 mf. What is the current in amperes?

**Solution:** $I = \frac{E}{X_c}$

$$\text{but } X_c = -\frac{1,000,000}{6.2832 \times 1000 \times 2}$$

$$= -\frac{1,000}{6.2832 \times 2}$$

$$= -79.5 \text{ ohms}$$

$$I = -\frac{10}{79.5}$$

$$= -.126 \text{ amperes, ans.}$$

(minus sign here means leading current)

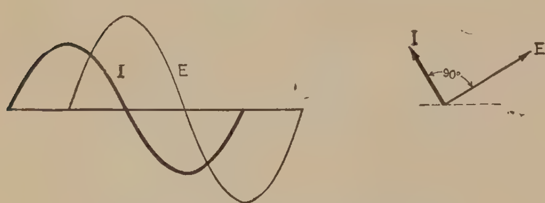



*Fig. 188—Effect of Capacity Reactance.*

### 93. Combination of Inductive and Capacity Reactances

If we wish to get the combined or total reactance of an inductance in series with a capacity, such as that shown in Figure 189, we may combine the reactances as follows:

$$X = X_L + X_c,$$

or, from formulas (50) and (53)

$$X = 6.2832\ fL - \frac{1,000,000}{6.2832\ fC} \quad \ldots \ (54)$$

Here the signs will take care of the neutralizing effect and if the calculated value of X is positive, the inductive reactance predominates; if negative, the capacity reactance predominates.

**Example:** Calculate the current in the circuit shown by Figure 189.

**Solution:**

With no resistance in the circuit—

$$I = \frac{E}{X} \text{ and}$$

$$X = X_L + X_c$$

$$= 6.2832\ fL - \frac{1,000,000}{6.2832\ fC}$$

$$X = 6.2832 \times 1000 \times .6 - \frac{1,000,000}{6.2832 \times 1000 \times 1}$$

$$= 3770 - 159$$

$$= 3611 \text{ ohms}$$

$$I = \frac{11}{3611} = .0028 \text{ amperes, ans.}$$

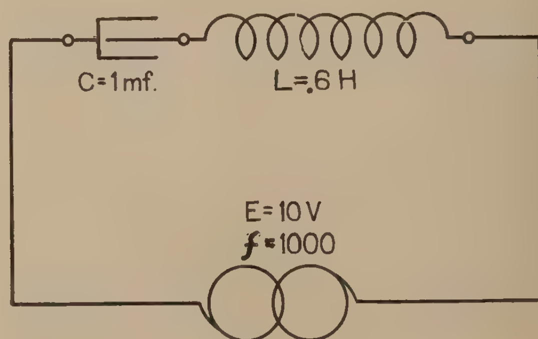



*Figure 189*

### 94. Impedance

To determine a way to combine reactance and resistance when we wish to evaluate the impedance, let us consider the relation between voltage and

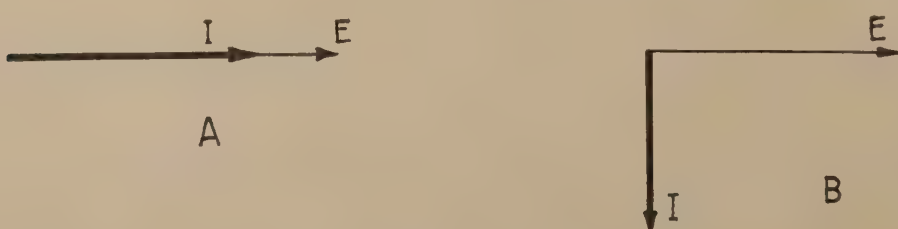



*Figure 190*

current under two conditions; first when a circuit contains pure resistance, and second, when it contains pure reactance. Under the first condition, we can represent the current, I, due to a voltage, E, as shown in Figure 190-A, and for the second condition, as shown in Figure 190-B. For the purpose of this discussion, the circuits are assumed to be such that IR = IX. If now we connect R and L in series and allow a voltage of 2E to act on the combination we may consider the resulting current as made up of two parts, one due to a voltage E acting on R, and the other due to a voltage E acting on L. The total current will be in a sense the sum of these two components, but the addition must be made vectorially as illustrated by Figure 191. Here since we have a right triangle, the hypotenuse is equal to the square root of the sum of the squares of the two legs, or calling the components $I_R$ and $I_X$, we have—

$$I = \sqrt{I_R^2 + I_X^2}$$


*Figure 191*

The voltage drop across R due to the flow of the current, I, is IR, and this drop is exactly opposite in phase with I. The drop across L is IX, with a phase relationship such that I leads IX by 90°. The latter will be clear if we refer again to the circuit of pure inductance pictured in Figure 185. Here the current lags the impressed voltage by 90°, and consequently leads the voltage drop, which is equal and opposite to the impressed voltage, by 90°.

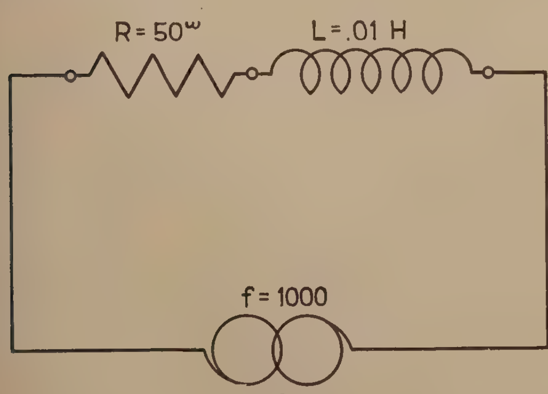



*Figure 192*

In our circuit containing both R and L, therefore, we have two component voltage drops, IR, and IX, 90° out of phase, the sum of which must be equal to the total impressed E.M.F. and exactly opposite in phase. Adding these components vectorially—

$$E = \sqrt{(IR)^2 + (IX)^2} = \text{total voltage drop,}$$

where E, in this case, is the total E.M.F. acting upon the combined circuit.

Now let us operate on this equation by dividing both sides by I and we have—

$$\frac{E}{I} = \frac{\sqrt{I^2 R^2 + I^2 X^2}}{I}$$

and simplifying this we have—

$$\frac{E}{I} = \frac{\sqrt{I^2 (R^2 + X^2)}}{I} = \frac{I\sqrt{R^2 + X^2}}{I}$$

but the I's will cancel and—

$$\frac{E}{I} = \sqrt{R^2 + X^2}$$

However, $\frac{E}{I} = Z$ in ohms from equation (48); therefore, we have

$$Z = \sqrt{R^2 + X^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (55)$$

which is the equation that shows the relation between impedance and its two components, i.e., as shown by the equation, impedance is the vector sum of resistance and reactance. Thus in Figure 192 the combined effect of the resistance and the reactance due to the inductance may be represented


*Fig. 193—Impedance with Resistance and Positive Reactance Components.*

by a vector diagram as shown by Figure 193 in which the reactance is shown as 90° ahead of the resistance. Similarly in Figure 194 the combined effect of resistance and capacity may be represented by a vector diagram shown by Figure 195 in which the reactance is shown as 90° behind the resistance.

In these diagrams R must be taken as in phase with the current and Z will be in phase with the impressed E.M.F.; consequently the angle Θ will represent the phase difference between the voltage and current, and with the adopted convention for direction of rotation and that for plotting time on the sinusoidal chart, will represent current lagging behind impressed E.M.F. for positive angle as shown in Figure 193, and current leading impressed E.M.F. for negative angle as shown in Figure 195.

We can now consider a simple series circuit with all three properties, or with resistance, inductance, and capacity as shown in Figure 196. Here we have two reactances acting in opposite phase as shown in Figure 197-A.

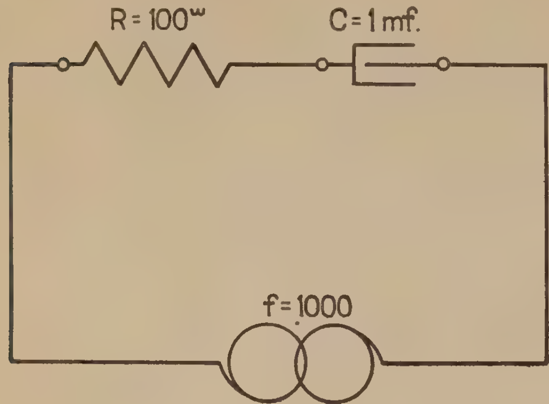



*Figure 194*

In constructing the triangle, $X_c$ must be considered as negative and subtracting from $X_L$ as shown in Figure 197-B. If $X_c$ is less than $X_L$, X will be positive, and if $X_c$ is greater than $X_L$ as shown in Figure 198, X will be negative.

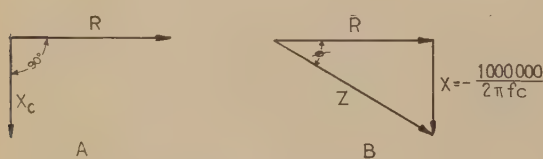



*Fig. 195—Impedance with Resistance and Negative Reactance Components.*

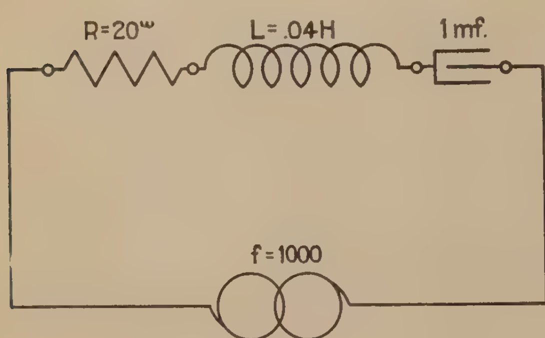



*Figure 196*

Having the relation of impedance to its component parts fixed in mind by the foregoing graphical construction, we can calculate its value in the same manner as we calculate the length of the hypotenuse of any right triangle, as has been explained. That is to say, we square both legs and take the square root of their sum. The equation then for impedance with resistance and inductance in series (as shown by Figures 192 and 193) is,

$$Z = \sqrt{R^2 + X_L^2} \quad \ldots\ldots\ldots\ldots \quad (56)$$

**Example:** In Figure 192, R = 50 ohms, f = 1000 cycles per second and L = .01 Henry. What is the value of the impedance in ohms?

**Solution:**

$$Z = \sqrt{R^2 + X_L^2}$$

$$\text{but } X_L = 2\pi fL$$

$$= 6.2832 \times 1000 \times .01$$

$$= 62.8$$

$$Z = \sqrt{(50)^2 + (62.8)^2}$$

$$= \sqrt{2500 + 3944}$$

$$= \sqrt{6444}$$

$$= 80.3 \text{ ohms, ans.}$$

Similarly for the impedance as shown by Figures 194 and 195,

$$Z = \sqrt{R^2 + X_c^2} \quad \ldots\ldots\ldots\ldots \quad (57)$$

**Example:** In Figure 194, R is 100 ohms, C is 1 mf. and f is 1000 cycles per second. What is the value of the impedance in ohms?

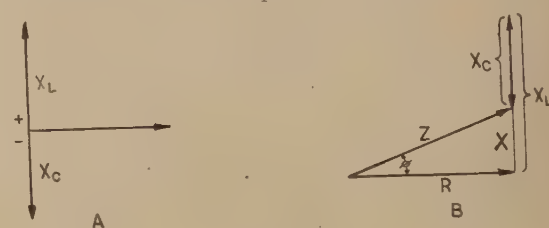



*Figure 197*

**Solution:**

$$Z = \sqrt{R^2 + X_c^2}$$

$$\text{but } X_c = -\frac{1{,}000{,}000}{2\pi fC}$$

$$= -\frac{1{,}000{,}000}{6.2832 \times 1000 \times 1}$$

$$= -159 \text{ ohms}$$

$$Z = \sqrt{(100)^2 + (-159)^2}$$

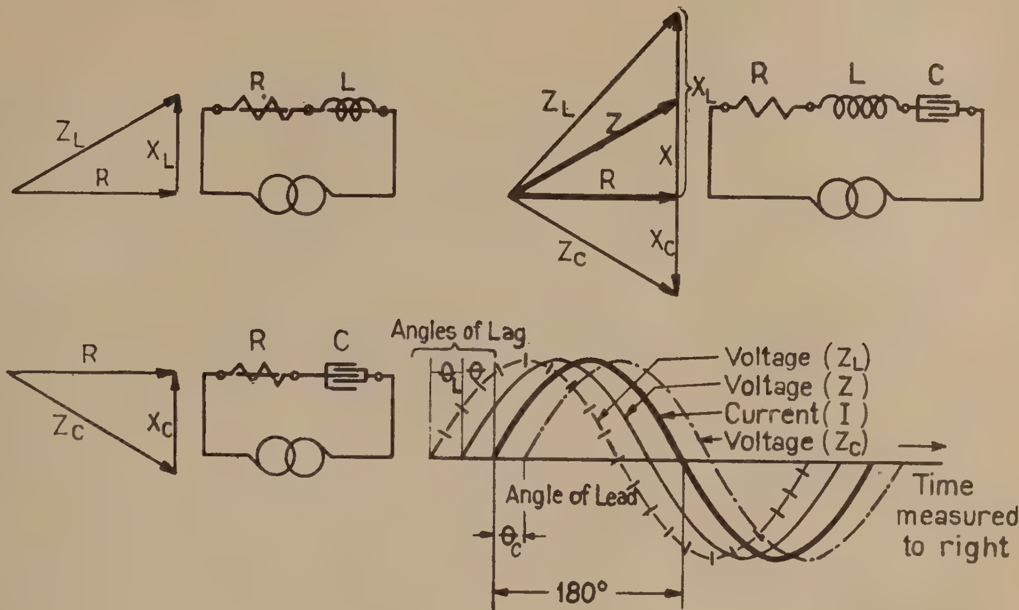
$$= \sqrt{10{,}000 + 25281}$$

$$= \sqrt{35{,}281}$$

$$= 188 \text{ ohms, ans.}$$

TABLE X

## Chart of Vector Relations




| Property | Reactance | Impedance | Phase Angle |
|---|---|---|---|
| Inductance (L) | $X_L = 2\pi fL$ | $Z_L = \sqrt{R^2 + X^2_L}$ | $\Theta_L = \text{Tan}^{-1} \frac{X_L}{R}$ |
| Capacity (C) | $X_C = -\frac{1,000,000}{2\pi fC}$ | $Z_C = \sqrt{R^2 + X^2_C}$ | $\Theta_C = \text{Tan}^{-1} \frac{X_C}{R}$ |
| Net Effect | $X = X_L + X_C$ | $Z = \sqrt{R^2 + X^2}$ | $\Theta = \text{Tan}^{-1} \frac{X}{R}$ |

NOTES:
1. Rotation is in counter-clockwise direction.
2. If lines $Z_C$, $Z_L$ or $Z$ represent phase of voltage, line R will indicate lead or lag of current and $\Theta_C$, $\Theta_L$ and $\Theta$ will be angle of lead or lag.
3. Power factor is cosine of phase angle (Power $=$ EI cos $\Theta$).
4. The impedance symbol is usually written $Z\underline{/\Theta}$, for example $Z\underline{/\Theta} =$ $15\omega\ \underline{/30^\circ}$, etc.

The foregoing are, of course, special cases but we may combine the inductive reactance and capacity reactance in one general equation for impedance as shown by equation (55) where

$$X = X_L + X_c = 2\pi fL - \frac{1{,}000{,}000}{2\pi fC}$$

Therefore,

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1{,}000{,}000}{2\pi fC}\right)^2} \quad (58)$$


*Figure 198*

**Example:** In Figure 196, R is 20 ohms, f is 1000 cycles per second, L is .04 Henry and C is 1 mf. What is the numerical value of the impedance in ohms?

**Solution:**

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1{,}000{,}000}{2\pi fC}\right)^2}$$

$$= \sqrt{(20)^2 + \left(6.28 \times 1000 \times .04 - \frac{1{,}000{,}000}{6.28 \times 1000 \times 1}\right)^2}$$

$$= \sqrt{(20)^2 + (251 - 159)^2}$$

$$= \sqrt{400 + 8464}$$

$$= \sqrt{8864}$$

$$= \quad 94 \text{ ohms, ans.}$$

In these calculations we have only determined the **numerical** value of the impedance. This does not completely describe it, however, since there could be any number of resistance, capacity and inductance combinations which would give the same numerical value of the impedance. It is essential, therefore, to include an additional factor which will indicate the relative magnitudes of the resistance and reactance components of the impedance in order to completely define it. This factor is the angle shown as $\Theta$ in Figures 197 and 198. Impedance is customarily expressed accordingly in the form $Z/\underline{\Theta}$ (Z at an angle $\Theta$) where Z is the magnitude of the impedance and $\Theta$ is the angle of lag or lead between any E.M.F. impressed across the impedance and the resultant current, and as may be seen from Figure 197 or 198 is equal to $\tan^{-1}\frac{X}{R}$ (the angle whose tangent is $\frac{X}{R}$). Also, by simple trigonometry we know that $R = Z \cos \Theta$ and $X = Z \sin \Theta$. Thus, with the impedance expressed in the form $Z/\underline{\Theta}$, it is completely defined and we may readily determine the magnitude of its resistance and reactance components.

# CHAPTER XVI

## THE SOLUTION OF A. C. NETWORKS

### 95. Series Networks

In Chapters I and II, means of solving direct current networks for the current values in the various branches were described. **The same methods and formulas apply to the solution of alternating current networks.** But in this case certain additional factors enter which, while not making the solutions any more difficult in principle, involve an increase in the amount of mathematical work required. This is due to the fact that whereas D. C. quantities (current, voltage and resistance) are of only one dimension and are therefore completely described by a single number giving their magnitude, the corresponding A.C. quantities are two-dimensional (i.e., vector quantities) and both their magnitudes and their time relationships with some reference point must be used in making calculations with them.

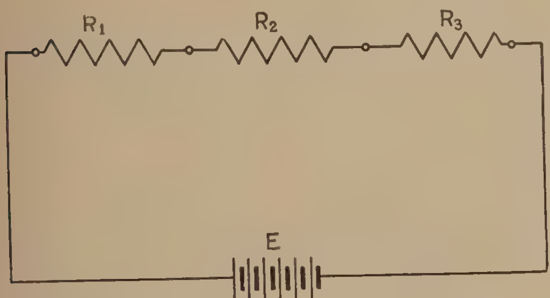



*Fig. 199—D. C. Circuit with Series Resistances.*

We learned in Chapter I that the total resistance in a D.C. series circuit such as is shown in Figure 199 is equal to the **arithmetic** sum of the individual resistances or

$$R = R_1 + R_2 + R_3, \text{ etc.} \qquad (4)$$

Similarly in an A.C. series circuit as shown in Figure 200 the total impedance is equal to the **vector** sum of the individual impedances or

$$\overline{Z} = \overline{Z_1} + \overline{Z_2} + \overline{Z_3} \quad \ldots\ldots\ldots\ldots\ldots \quad (59)$$

the bars over the impedance symbols meaning that they are vectors and to be treated accordingly in performing the indicated additions.

To graphically illustrate the application, let us assume that $Z_1 = 10$ ohms with $\Theta_1 = 30^\circ$, $Z_2 = 15$ ohms with $\Theta_2 = 45^\circ$ and $Z_3 = 20$ ohms with $\Theta_3 = 60^\circ$; we then have the three vectors represented by Figure 201-A which when added give the value of Z as shown in Figure 201-B. If we should represent not only the impedance vectors but the resistance and reactance components as well, we should find that each group of components adds algebraically as shown by Figure 202, and by comparing Figure 202-C with Figure 202-B we find that the length of X is the sum of $X_1$, $X_2$ and $X_3$ and likewise the

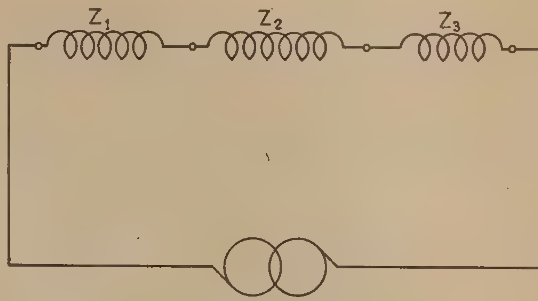



*Fig. 200—A. C. Circuit with Series Impedances.*

length of R is the sum of $R_1$, $R_2$ and $R_3$. Therefore since—

$$Z = \sqrt{R^2 + X^2}, \text{ we have}$$

$$Z = \sqrt{(R_1 + R_2 + R_3)^2 + (X_1 + X_2 + X_3)^2} \quad . \quad (60)$$

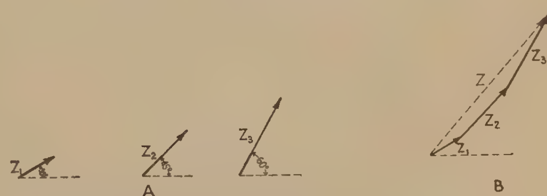



*Fig. 201—Vector Method of Adding Impedances.*

In order to evaluate Z it remains then to find the values of the components of each individual impedance, which is obtained by multiplying the value of the particular impedance by the proper function of the angle.

**Example:** Find the total impedance of the circuit in Figure 200 using the values for $Z_1$, $Z_2$ and $Z_3$ given above.

**Solution:**

$$X = Z \sin \Theta$$
$$R = Z \cos \Theta$$

This gives $X_1 = 10 \times \frac{1}{2} = 5$ ohms
$R_1 = 10 \times .866 = 8.7$ ohms

Likewise other values can be determined and—

$X_2 = 10.6$ ohms
$R_2 = 10.6$ ohms
$X_3 = 17.3$ ohms
$R_3 = 10.$ ohms

Applying equation (60)—

$$Z = \sqrt{(R_1 + R_2 + R_3)^2 + (X_1 + X_2 + X_3)^2}$$
$$= \sqrt{(8.7 + 10.6 + 10)^2 + (5 + 10.6 + 17.3)^2}$$
$$= \sqrt{(29.3)^2 + (32.9)^2}$$
$$= 44.0 \text{ ohms}$$
$$\Theta = \tan^{-1} \frac{32.9}{29.3}$$
$$= \tan^{-1} 1.12$$
$$= 48°$$

Therefore $Z = 44\underline{/48°}$ ohms, ans.

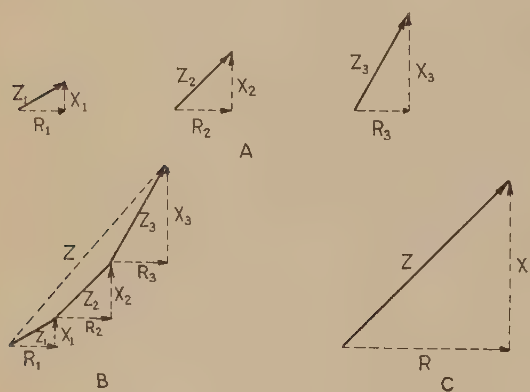



*Figure 202*

The foregoing calculation covers a general case. In practice, however, we usually have given the inductance, capacity and resistance values rather than the individual impedances with their respective angles.

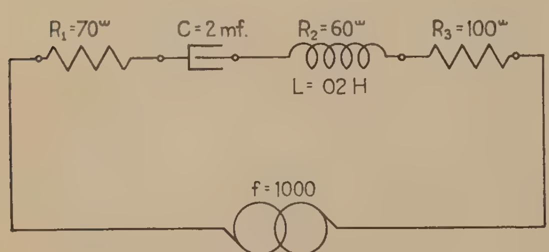



*Figure 203*

**Example:** Find the impedance of the series circuit shown by Figure 203.

**Solution:**

$$Z = \sqrt{(R_1 + R_2 + R_3)^2 + (X_1 + X_2)^2}$$

where $X_1 = -\dfrac{1{,}000{,}000}{2\pi fC}$

$$= -\frac{1{,}000{,}000}{6.28 \times 1000 \times .2}$$
$$= -796 \text{ ohms.}$$

and $X_2 = 2\pi fL$

$$= 6.28 \times 1000 \times .02$$
$$= 125.6 \text{ ohms.}$$

Then

$$Z = \sqrt{(70 + 60 + 100)^2 + (-796 + 125.6)^2}$$
$$= \sqrt{(230)^2 + (-670.4)^2}$$
$$= 709 \text{ ohms.}$$

and $\Theta = \tan^{-1} \dfrac{-670.4}{230}$

$$= \tan^{-1} -2.9 \text{ or } \Theta = -71°,$$

whence $Z = 709\underline{/-71°}$, ans.

### 96. Parallel and Series-parallel Networks

In Chapter II we learned that the combined resistance of two parallel resistances was equal to

$$R = \frac{R_1 R_2}{R_1 + R_2} \qquad (8)$$

or that if more than two resistances are in parallel the combined resistance may be found by adding together the reciprocals of each resistance (called conductance) and taking the reciprocal of this value. That is—

$$G = G_1 + G_2 + G_3 \qquad (10)$$

or $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}$

Now if we substitute impedance for resistance in the above equations they will still hold for the A.C. case, providing that we remember that impedances are vector quantities. Thus for two impedances in parallel we may write the value of the combined impedance as

$$\overline{Z} = \frac{\overline{Z_1}\ \overline{Z_2}}{\overline{Z_1} + \overline{Z_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (61)$$

or for more than two in parallel,

$$\frac{1}{\overline{Z}} = \frac{1}{\overline{Z_1}} + \frac{1}{\overline{Z_2}} + \frac{1}{\overline{Z_3}} \text{ etc.} \quad \ldots\ldots\ldots \quad (62)$$

which latter may also be written—

$$\overline{Y} = \overline{Y_1} + \overline{Y_2} + \overline{Y_3}, \text{ etc.} \quad \ldots\ldots\ldots \quad (63)$$

where Y represents the reciprocal of impedance and is called **admittance.**

The mathematical solution of such equations as (61) requires that the vectors be expressed in the standard algebraic form, i.e. $\overline{Z} = Z/\underline{\Theta} = R + jX$.

The use of this notation makes possible the direct application of the same formulas as those used in D.C. calculations to the solution of A.C. networks. As an example let us determine the current delivered by the generator of Figure 204 and the phase angle of this current with the generator E.M.F.

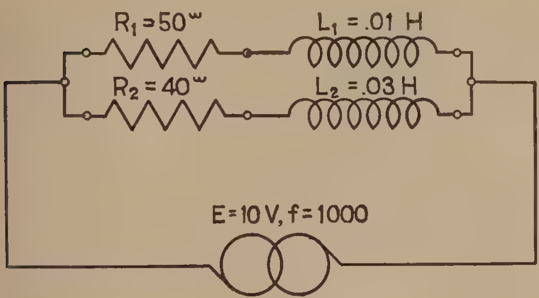



*Figure 204*

By Ohm's law we know that the total current delivered by the generator is

$$I = \frac{E}{Z\,/\underline{\Theta}}$$

where $Z\,/\underline{\Theta}$ is the total impedance of the circuit and consists of the net impedance of the two parallel paths whose individual impedances may be indicated as $Z_1\,/\underline{\Theta_1}$ and $Z_2\,/\underline{\Theta_2}$. Then from the usual formula for parallel circuits—

$$Z\,/\underline{\Theta} = \frac{Z_1/\underline{\Theta_1} \times Z_2/\underline{\Theta_2}}{Z_1/\underline{\Theta_1} + Z_2/\underline{\Theta_2}} \qquad \ldots\ldots\ldots \text{(61)}$$

The first step will be to find the values of $Z_1/\underline{\Theta_1}$ and $Z_2/\underline{\Theta_2}$. We know that

$$\Theta_1 = \tan^{-1} \frac{X_1}{R_1}$$

where $R_1 = 50$ ohms

and $X_1 = 2\pi f L_1 = 6.28 \times 1000 \times .01 = 62.8$ ohms

Then $\Theta_1 = \tan^{-1} \frac{62.8}{50} = \tan^{-1} 1.255 = 51^\circ\,27'$

From which $Z_1 = \frac{R_1}{\cos \Theta_1} = \frac{50}{\cos 51^\circ\,27'} = \frac{50}{.6232} =$ 80.3 ohms

Impedance of branch 1 $= Z_1/\underline{\Theta_1} = 50 + j\,62.8 = 80.3\,/\underline{51^\circ\,27'}$

Likewise $R_2 = 40$ ohms

$$X_2 = 2\pi f L_2 = 6.28 \times 1000 \times .03 = 188.2 \text{ ohms}$$

$$\Theta_2 = \tan^{-1} \frac{188.2}{40} = \tan^{-1} 4.71 = 78^\circ 1'$$

$$Z_2 = \frac{40}{\cos 78^\circ 1'} = \frac{40}{.2076} = 193.0 \text{ ohms}$$

Impedance of branch 2 $= Z_2/\underline{\Theta_2} = 40 + j\,188.2 = 193.0\,/\underline{78^\circ 1'}$

Then using formula (61) and expressing the vectors of the numerator in the $Z\,/\underline{\Theta}$ form since multiplication is involved, and the vectors of the denominator in the $R + jX$ form since addition is involved, we have—

$$Z\,/\underline{\Theta} = \frac{Z_1\,/\underline{\Theta_1} \times Z_2\,/\underline{\Theta_2}}{(R_1 + jX_1) + (R_2 + jX_2)}$$

$$= \frac{Z_1\,Z_2\,/\underline{\Theta_1 + \Theta_2}}{(R_1 + R_2) + j\,(X_1 + X_2)}$$

$$= \frac{80.3 \times 193.0\,/\underline{51^\circ 27' + 78^\circ 1'}}{(50 + 40) + j\,(62.8 + 188.2)}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{90 + j\,251.0}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{\dfrac{90}{\cos\left(\tan^{-1}\dfrac{251.0}{90}\right)}\,\bigg/\underline{\tan^{-1}\dfrac{251.0}{90}}}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{\dfrac{90}{\cos\,(\tan^{-1} 2.79)}\,/\underline{\tan^{-1} 2.79}}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{\dfrac{90}{\cos\,70^\circ 17'}\,/\underline{70^\circ 17'}}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{\dfrac{90}{.3374}\,/\underline{70^\circ 17'}}$$

$$= \frac{15500\,/\underline{129^\circ 28'}}{267\,/\underline{70^\circ 17'}}$$

$$= \frac{15500}{267} \underline{/129^\circ 28' - 20^\circ 17'}$$

$$= 58.0 \underline{/59^\circ 11'}$$

And
$$I = \frac{E}{Z \underline{/\Theta}} = \frac{10}{58 \underline{/59^\circ 11'}}$$

$$= \frac{10}{58} \underline{/0^\circ - 59^\circ 11'} = .1725 \underline{/-59^\circ 11'}$$

Thus we find that the generator will deliver a current of .1725 amperes and this current will lag the generator voltage by 59°11′.

With a little practice it will be found that several of the detailed steps given above can be performed in a single operation. This may be illustrated by solving the circuit of Figure 205 to find the current delivered by the generator and its phase relationship with the E.M.F.

Solution:

$$Z_1 = R_1 + j\,X_1$$

$$X_1 = -\frac{10^6}{2\,\pi f C_1} = -\frac{1{,}000{,}000}{6.28 \times 1000 \times 1} = -159.3 \text{ ohms}$$

$$Z_1 = 20 - j\,159.3 = 160.7 \underline{/-82^\circ 51'}$$

$$Z_2 = R_2 + j\,X_2 = 72 + j\,0 = 72 \underline{/0^\circ}$$

$$Z_A = \frac{Z_1\,Z_2}{Z_1 + Z_2} = \frac{160.7 \underline{/-82^\circ 51'} \times 72 \underline{/0^\circ}}{20 - j\,159.3 + 72 + j\,0}$$

$$= \frac{11{,}570 \underline{/-82^\circ 51'}}{92 - j\,159.3} = \frac{11{,}570 \underline{/-82^\circ 51'}}{184 \underline{/-60^\circ 1'}}$$

$$= 62.8 \underline{/-22^\circ 50'} = 58.0 - j\,24.4$$

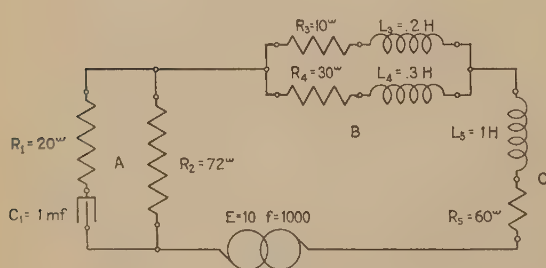



*Figure 205*

$$Z_3 = R_3 + j\,X_3$$

$$X_3 = 2\pi f L_3 = 6.28 \times 1000 \times .2 = 1256$$

$$Z_3 = 10 + j\,1256 = 1256 \underline{/89^\circ 33'}$$

$$Z_4 = R_4 + j\,X_4$$

$$X_4 = 2\,\pi\,f\;L_4 = 6.28 \times 1000 \times .3 = 1884$$

$$Z_4 = 30 + j\,1884 = 1884 \underline{/89^\circ 5'}$$

$$Z_B = \frac{Z_3\,Z_4}{Z_3 + Z_4} = \frac{1256 \underline{/89^\circ 33'} \times 1884 \underline{/89^\circ 5'}}{10 + j\,1256 + 30 + j\,1884}$$

$$= \frac{2{,}365{,}000 \underline{/178^\circ 38'}}{40 + j\,3140}$$

$$= \frac{2{,}365{,}000 \underline{/178^\circ 38'}}{3140 \underline{/89^\circ 16'}}$$

$$= 753 \underline{/89^\circ 22'} = 8 + j\,753$$

$$Z_5 = R_5 + j\,X_5$$

$$X_5 = 2\pi f L_5 = 6.28 \times 1000 \times .1 = 628$$

$$Z_5 = 60 + j\,628$$

The total impedance $Z = Z_A + Z_B + Z_5$

$$Z = 58.0 - j\,24.4 + 8 + j\,753 + 60 + j\,628$$

$$= 126.3 + j\,1356 = 1360 \underline{/84^\circ 40'}$$

$$I = \frac{E}{Z} = \frac{10}{1360 \underline{/84^\circ 40'}} = .00735 \underline{/-84^\circ 40'}$$

The current delivered by the generator has a value of .00735 amperes—and lags the impressed voltage by 84°40′.

### 97. Alternating Current Resistance

In alternating current networks, the apparent resistance of a particular piece of apparatus is often quite different from its direct current or true resistance. As shown by Table VII, the resistance offered to alternating current flow may be much greater than that offered to direct current flow; furthermore, in such cases the value of the resistance depends to some extent on the alternating current frequency. We find, then, that **not only the reactance component of an impedance but its resistance component as well may be a function of the frequency.**

"Alternating current resistance", so called to distinguish it from direct current or true resistance, represents not only the actual resistance of the conductor used to wind a coil but includes also a factor due to the power losses within the iron core. That is to say, when a current flows through a coil winding and establishes a strong magnetic field in the core first in one direction and then in the other, there are certain power losses within the iron due to a heating effect. This is caused in part by hysteresis and in part by small currents induced in the iron itself as a conductor and called "eddy currents". The total power loss in the coil includes not only the heat losses due to the resistance of the coil winding but also the core losses, and since any power loss can be expressed in the form of the

equation $P = RI^2$, with a known value of I, we assume that the winding has in effect a resistance which gives the total power loss, or has a value that satisfies the above equation. But it so happens that the part of the power loss that is due to the iron core increases with the frequency. Therefore, we should expect the A.C. resistance for a high frequency to be greater than the A.C. resistance for a low frequency.

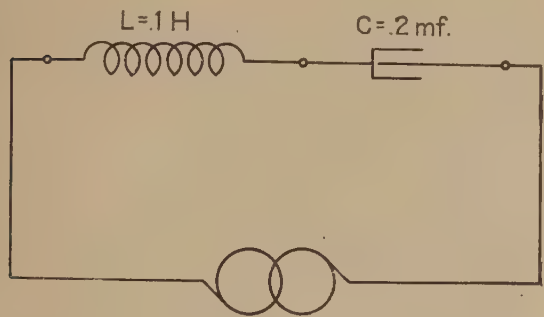



*Figure 206*

## 98. Resonant Circuits

If a series circuit consists of capacity in series with an inductance, as shown by Figure 206, there will be some frequency at which the negative reactance due to the capacity, or $X_c$ (which equals — $1{,}000{,}000/2\pi fC$) becomes equal but opposite in value to $X_L$ (which equals $2\pi fL$), and if the resistance is negligible, the impedance becomes zero, or in effect there is a short circuit on the generator. This may be understood from the equation—

$$X = 2\pi fL - \frac{1{,}000{,}000}{2\pi fC} \quad \ldots\ldots\ldots\ldots \quad (54)$$

since an increase in the value of the frequency increases the value of the first term and decreases the value of the second term. Consequently there must be some one frequency where the two terms are equal in value and will cancel, thereby making X equal to zero. **This is called the frequency to which the circuit is resonant** and equation (54) becomes

$$0 = 2\pi fL - \frac{1{,}000{,}000}{2\pi fC}$$

from which the value of f can be determined in terms of the inductance and capacity by simplifying the equation and is as follows:

$$f_r = \frac{1000}{2\pi\sqrt{LC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (64)$$

$f_r$ being the symbol for resonant frequency.

**Example:** To what frequency is the circuit shown by Figure 206 resonant if C is 2 mf. and L is .1 H?

**Solution:**

$$f_r = \frac{1000}{6.28\sqrt{.1 \times .2}}$$

$$= \frac{1000}{6.28 \times \sqrt{.02}}$$

$$= \frac{1000}{6.28 \times .141}$$

$= 1134$ cycles per second, ans.

The resonant principle in its broadest applications, or rather the practice of neutralizing capacity reactance with inductive reactance, has numerous and interesting uses in connection with all communication circuits. There are three classes of such applications in particular which are very common. The first of these is the use of a condenser of proper capacity in series with a telephone receiver winding, repeating coil winding, or other winding having inductance where it is desired to increase the current flow through the receiver or coil winding. The condenser of a common battery subset, for example, increases the current flow through the receiver in this way, and similarly most operators' telephone sets have a 2 mf. condenser associated with the induction coil. Also telephone receivers, when used in connection with testing apparatus employing a single frequency are often connected with a condenser in series in order that the receiver circuit will act as a plain resistance.

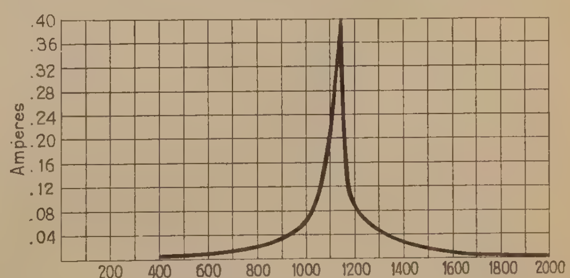



*Fig. 207—Current Values Illustrating Resonant Frequency.*

The second application of the principle is the so-called "tuned" circuit, or the resonant circuit used for high selectivity. It is an arrangement whereby the circuit has a much lower impedance to some particular frequency than to any other frequency, and if a band of frequencies is impressed, it selects, so to speak, a high current for the particular frequency but permits only a negligible current for any other frequency to flow. Figure 207 illustrates the selectivity of the resonant circuit illustrated by Figure 206, where the generator is replaced by a source of E.M.F. giving a band of frequencies instead of a single frequency. In this figure we have assumed an impressed E.M.F. of 10 volts for each

frequency of the band and a resistance of 25 ohms for the inductance in order to have a more practicable condition where the circuit has some resistance. The peak current value of the curve depends entirely upon the resistance value, for at this peak the positive and negative reactances exactly neutralize each other and the current flow is determined solely by the resistance.

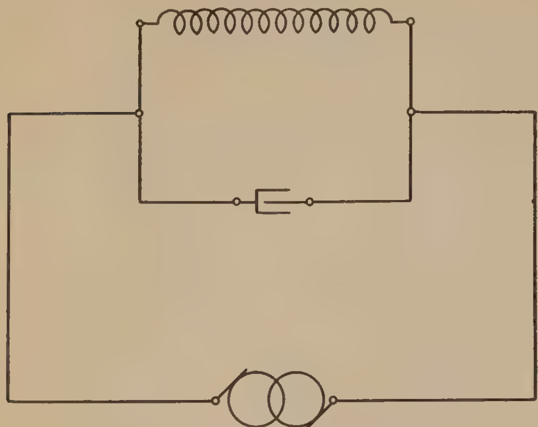


*Fig. 208—Anti-Resonant Circuit.*

Another connection of the tuned circuit is that shown by Figure 208. This is called the **"anti-resonant"** connection. For this condition, when the positive reactance is equal and opposite to the negative reactance the combined impedance presented to the generator is extremely great and there is the smallest conceivable load on the generator. In other words, the generator circuit is practically open. At the same time there must be a current flowing through the inductance determined by dividing the voltage of the generator by the impedance of this branch, and similarly there must be a current flowing through the condenser which can be determined in the same way. These currents, however, are equal in value, but are flowing in opposite directions, thereby neutralizing each other in the lead to the generator giving an open circuit in so far as the generator is concerned, but a circuit equal to either the inductance or capacity alone connected to the generator in so far as either of the branches is concerned. The physical explanation here is that a current is oscillating around through the inductance and condenser with the E.M.F. of the generator merely sustaining this oscillation. Of course, since the inductance must have some resistance there will be an $RI^2$ power loss in the inductance, and it would never be possible to have the theoretical case where there is an absolute zero current flow from the generator. In other words, there is no such thing as what we might call "perfect anti-resonance" where no energy is supplied by the generator and a current is maintained indefinitely by energy oscillating back and forth from the condenser to the coil.

Perhaps the most widely known application of both resonant and anti-resonant tuned circuits is in connection with radio sending and receiving sets. The most interesting from our viewpoint is, perhaps, the carrier application which we cannot discuss here since we have not made a study of carrier circuit operation. However, the composite ringer circuit, which we have already studied and which is shown in connection with Figure 168, is a good illustration. Here the 150-E relay and the J-1 relay are both bridged connections, but the 150-E relay must respond to 135 cycle frequency and the J-1 relay must respond to 20 cycle frequency. On the other hand, the entire bridged combination must have very high impedance to the voice frequency band or else the bridge will form a shunt to the talking connection, thereby giving an appreciable transmission loss. Analyzing first the 20 cycle case, let us assume an E.M.F. impressed across the entire bridge or from one side of the talking circuit to the other. This E.M.F. is impressed across one winding of the ½ 44-B retard coil and the winding of the J-1 relay in series with a 2 mf. condenser. If we should calculate the impedance of this circuit for various frequencies and by application of the formula $I = E/Z$ plot a curve similar to that shown by Figure 207, we should find that the current peak is close to 20 cycles, and that the current at 1,000

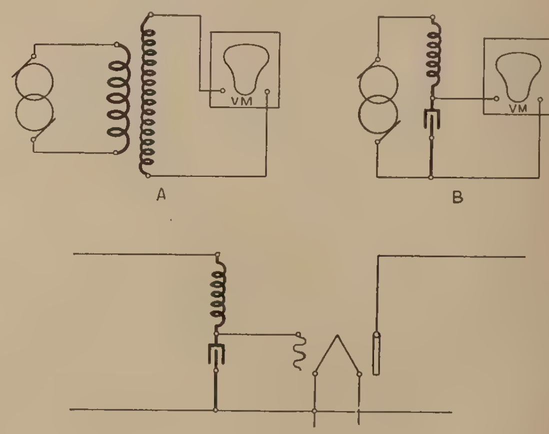



*Fig. 209—Circuit Connections For Increasing Voltage.*

cycles is so small as to be negligible. We should further find that the current, even at 135 cycles, is so low that very little of the 135 cycle energy is shunted by this 20 cycle bridge. Let us now analyze the other bridge through the winding of the ½ 44-B coil designated as 3-4, the ½ mf. condenser and the 150-E relay winding shunted by a 1 mf. condenser. We shall find that this bridge has the feature illustrated by Figure 208 in that the small 135 cycle impressed E.M.F. would cause an appreciable current to flow or rather to oscillate through the relay winding and 1 mf. condenser. Futhermore, the ½ mf. condenser in series with one winding of

the 44-B retard coil, has a relatively high impedance to all currents but the 135 cycle current and thus receives incoming rings efficiently, yet neither shunts the J-1 relay nor causes appreciable transmission loss.

The third common use of the resonant principle is a simple substitute for a step-up transformer where an E.M.F. (with little current drain) is desired which is greater than the impressed E.M.F. An example of such use is in connection with some vacuum tube circuits where the operation depends

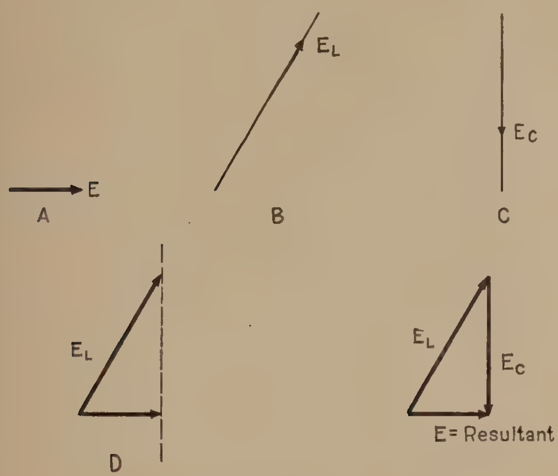



*Figure 210*

upon the impressed E.M.F. on the grid (which is practically an open circuit) rather than upon the current strength of the incoming energy. Figure 209 illustrates this principle. Here Sketch "A" illustrates the step-up transformer while Sketch "B" shows how a resonant circuit can be used to greatly increase the E.M.F. of the generator at a single frequency, thereby accomplishing the same result as the transformer. If a voltmeter is connected across the condenser alone it will be found that the voltage is many times that of the generator at the resonant frequency. Sketch "C" illustrates the connection of the grid circuit for securing a higher potential than that which is impressed from the line. Just how this circuit actually steps up the impressed voltage is best understood by vectorial analysis. Let us assume that Figure 210-A represents the impressed E.M.F. vector. Since this is a closed circuit we know that the vector sum of the voltage drops must be equal to the impressed E.M. F. Therefore, the voltage across the inductance added vectorially to the voltage across the condenser must be equal to the vector "A", but the voltage across the inductance is an induced E.M.F. and is a nearly vertical vector such as that represented by "B". It would be entirely vertical were it not for the resistance of the inductance, but due to the presence of the resistance must act through an angle which is that of the impedance rather than that of the positive reactance. The vector representing the drop across the condenser is a vertical vector acting downward and is illustrated by "C". The three vectors when added must make a closed triangle, with vector "A" as the resultant. Therefore, if vector "A" is placed adjacent to vector "B" as shown in Sketch "D" and vector "C" is drawn in an absolutely perpendicular direction so as to complete the diagram, we find that the values of vectors "B" and "C" must be much greater than that of the resultant "A" since they are so nearly opposite in direction.

# REPEATING COILS AND TRANSFORMERS

## 99. Mutual Induction

The inductive effects discussed in Chapter IX dealt with the magnetic interlinkages from one turn of a coil winding to the other turns of the same winding. We defined the effects coming from such magnetic interlinkages as "self-inductance". The current resulting from the induced E.M.F. was superposed upon the current resulting from the impressed E.M.F.

In practice we may experience inductive effects in circuits other than the one in which the current due to the impressed E.M.F. is flowing; **that is to say, two coils may be so related that the magnetic lines of force established by a current flowing in the first coil may cut the turns of the second coil (which may be connected to an entirely different circuit) in the same way that lines of force established by any one turn of a single coil cut each and every other turn of the same coil.** This effect is called **mutual induction** and the property of the electrical circuit that is responsible for the effect is known as its "**mutual inductance**".

## 100. Theory of the Transformer

In the study of magnetism we found that a wire in which a current is flowing is always surrounded by a magnetic field. This field, when created by a current establishing itself in the conductor, grows outwardly from the wire as the current increases.

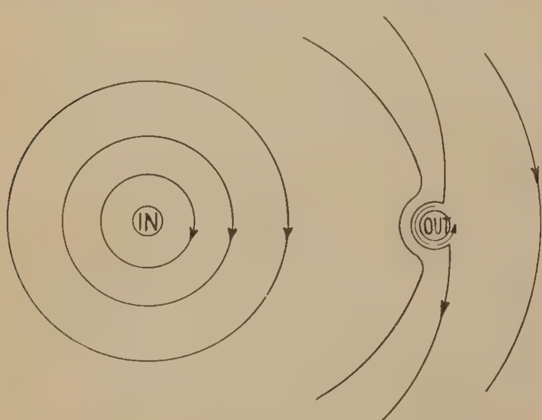



*Figure 211*

Figure 211 shows a group of lines of force around a conductor (shown in cross-section) in which the current is increasing in value. If a second conductor is in its vicinity, it will be cut by these lines moving outward from the current carrying conductor, and in the same manner that stationary lines of force seem to break and wrap themselves around a moving conductor (Figure 71), moving lines of force will break and wrap themselves around the stationary conductor, for although the lines of force cut the conductor instead of the conductor cutting the lines of force, the motion is merely relative. This phenomenon induces an E.M.F. in the second conductor, which, as illustrated in the figure, will establish a current flowing outward, or opposite to that in the primary conductor. This induced current will cease to flow, however, when the current in the first conductor reaches its maximum value, or at any other instant when it may have a steady, unchanged flow, since the magnetic field has become stationary and the lines of force move neither outward nor inward for a steady current value.


*Figure 212*

But if the current in the first conductor is decreased, we have the reverse condition or that shown in Figure 212. Here lines of force, instead of expanding and moving outward, are contracting and moving inward, cutting the second conductor as formerly, but now the current induced is in the opposite direction. At this time the current is in the same direction in the second conductor as in the first. This law for induced E.M.F. may be expressed as follows: **For any two parallel conductors, a current in one increasing in value induces an E.M.F. in the other, tending to make a current flow in the opposite direction, and a current decreasing in one will induce an E.M.F. in the other, tending to make a current flow in the same direction.**

If, instead of the two single conductors shown in Figures 211 and 212, we consider two separate coils, one inside the other, as in Figure 213, and if we call

the one in which the original current is flowing the "primary", which in this case we may represent by the inside coil, and the other the "secondary", we shall find that a strong magnetic field is established by an increasing current in the primary. This will cut the entire group of conductors represented by the turns of the secondary, thereby inducing appreciable potential in the secondary. The ordinary telephone induction coil operates in this manner. The primary when connected in series with the transmitter must carry a current which decreases and increases in value in response to the varying resistance of the transmitter, and consequently will induce an alternating current in the secondary of the coil.

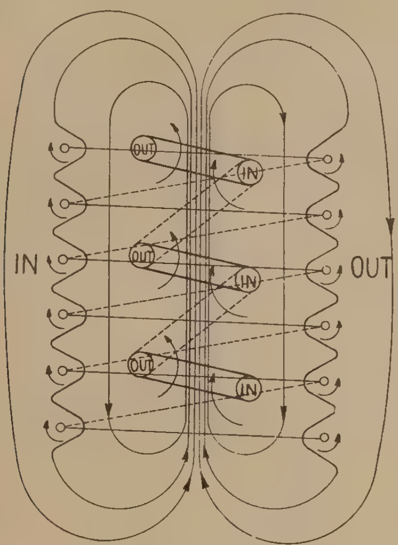



*Figure 213*

If now the two separate coils of Figure 213 are wound on the same iron core in the manner indicated by Figure 214, the effect will be intensified because, since the iron offers a path of low resistance to the magnetic flux, the total number of lines of force will be greatly increased and all of the lines set up by the primary winding, P, will cut all of the turns of the secondary winding, S.

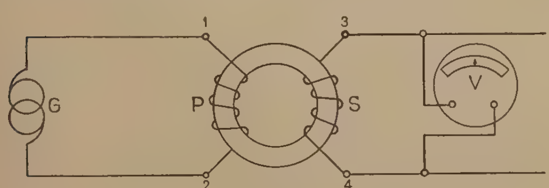



*Figure 214*

If the windings "P" and "S" have the same number of turns and both the coils and iron core are constructed so as to have negligible energy losses, we find that the voltmeter reading is the same when connected across the terminals of "S" as when connected across the terminals of "P". In other words, the induced E.M.F. of the secondary winding is equal to the impressed E.M.F. of the primary winding. Such a device is called an ideal transformer of **unity** ratio.

If, now, we should **increase** the number of turns of the secondary winding "S" we would find that the voltmeter reading would be greater on the secondary than on the primary side of the transformer. If we should **decrease** the number of turns of the winding "S" the effect would be reversed. We have here a means, therefore, of controlling the voltage applied to a load; we may effectively **increase** or **decrease** the generator voltage by a proper choice of transformer. If a transformer has a greater number of turns on the secondary than on the primary so that the voltage is **increased,** it is called a "step-up" transformer. If it has a less number of turns on the secondary than on the primary so that the voltage is **decreased,** it is called a "step-down" transformer. For an ideal transformer the voltage when measured across the two windings is directly proportional to the number of turns. This relation is expressed by the equation:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (65)$$

We may explain this relation between the number of turns and voltage by our original law governing inductive effects, which states that **the induced voltage is proportional to the rate of cutting lines of force.** Each time the alternating E.M.F. in the primary completes a cycle, it establishes a magnetic flux in the iron core which collapses to be established in the opposite direction, to again collapse, etc. This flux must cut each and every turn about the iron core. In doing so, for the ideal case where there is no loss due to magnetic leakage, etc., the same voltage is induced in each individual turn, which we may represent by the symbol "v". Now, the voltage measured across the secondary (with no load connected to the secondary) is merely the sum of these individual turn voltages or—

$$V_S = N_S \times v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (66)$$

when $N_S$ is the number of turns on the secondary.

In the primary the induced E.M.F. must be exactly equal and opposite to the impressed E.M.F. since in the case of the ideal transformer we have considered the E.M.F. due to RI drop as negligible. This could be expressed by a similar formula to equation (66), thus—

$$V_P = N_P \times v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (67)$$

Since "v" is the same in both equations (66) and (67), we may derive equation (65) by dividing (67) by (66).

In Figure 214 the current being supplied by the generator is negligible inasmuch as we have considered the transformer as having no energy losses. If, however, a load in the form of a shunting impedance is connected to its secondary as shown by Figure 215, the induced E.M.F. in the winding "S" causes a current to flow through the impedance $Z_S$, and from equation (48) this current can be expressed—

$$I_S = \frac{V_S}{Z_S}$$

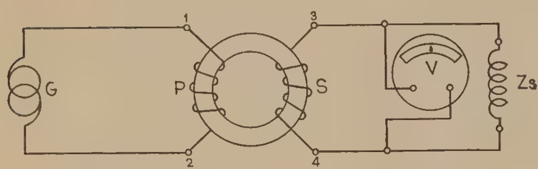



*Figure 215*

When this current starts to flow through the load $Z_s$, and through the winding "S", it will establish other lines of force in the same transformer core which oppose those established by the current in the winding "P". This will tend to neutralize the magnetic field through the iron core, thereby tending to counteract the inductance of the winding "P" and tending to make it more nearly like a plain resistance. With the induced E.M.F. in the winding "P" reduced, a greater current will flow from the generator through this winding, thus again increasing the flux in the iron core, so that finally there are produced the same induced E.M.F. effects as in the case of the transformer on open circuit. We, therefore, find that the transformer adjusts itself to any load that may be connected to the secondary just as if an **equivalent** load were connected directly to the generator i.e., the current supplied by the generator increases with an increase of current in the secondary of the transformer.

This current, however, is not necessarily the same in the primary as in the secondary, but like the voltage depends upon the ratio of the number of turns of the primary to the number of turns of the secondary. The relation between current values, however, is the inverse ratio of the number of turns, or in other words, the winding having the greater number of turns has a proportionately smaller current. This is seen when we consider that the flux in the ring depends upon the current value times the number of turns, and the flux established by one coil balances that established by the other—

$$N_p \times I_p = N_s \times I_s \text{ or } \frac{I_s}{I_p} = \frac{N_p}{N_s} \quad \ldots\ldots\ldots \quad (68)$$

The same relation can be determined in another way. We know from the law of conservation of energy that the energy existing in the secondary circuit can never exceed, but for an ideal transformer will be just equal to, the energy of the primary circuit, where since—

$$P_p = P_s \text{ and } P = EI,$$

we have—

$$V_s I_s = V_p I_p$$

from which—

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} \text{ or } \frac{I_s}{I_p} = \frac{N_p}{N_s} \quad \ldots\ldots\ldots\ldots \quad (68)$$

Though we find that connecting the load $Z_s$ to the secondary of the circuit causes the generator to furnish a current output in much the same way as if a load were connected across the generator, it does not follow that the same current flows through the load $Z_s$ with the transformer inserted between the generator and $Z_s$ as would flow if $Z_s$ were connected directly to the generator without the transformer. We have just seen that the voltages measured on the two sides of the transformer are directly proportional to the number of turns, and we know, moreover, from equation (48) that—

$$Z_s = \frac{V_s}{I_s}$$

But the current and voltage of the generator with the transformer inserted between it and the load $Z_s$ are $V_p$ and $I_p$, respectively, so that were we to connect a load directly to the generator that would absorb the same energy output, it would be of the value—

$$Z_p = \frac{V_p}{I_p}$$

We find, then, that—

$$\frac{Z_p}{Z_s} = \frac{V_p}{I_p} \div \frac{V_s}{I_s} = \frac{V_p}{I_p} \times \frac{I_s}{V_s} = \frac{V_p}{V_s} \times \frac{I_s}{I_p} = \frac{N_p}{N_s} \times \frac{N_p}{N_s}$$

or—

$$\frac{Z_p}{Z_s} = \left(\frac{N_p}{N_s}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (69)$$

Inequality ratio transformers may be rated either according to their voltage ratios, "step-up" or "step-down" as the case may be, or in accordance with their impedance ratios. In power work where transformers are primarily used to change the voltage of the system, the rating is on the voltage basis, but in telephone work where inequality transformers are used in most cases primarily to match unequal impedances, as will be explained later, they are rated in accordance with their impedance ratios.

Before taking up specific uses of the transformer, let us review in general what its presence in Figure 215 has or may have accomplished:

a. The characteristics of the electrical energy may have been changed, or we might say its state may have been "transformed", inasmuch as in the primary circuit we may have had high current and low voltage, while in the secondary circuit we may have had low current and high voltage, or vice versa, depending upon whether the transformer was a "step-up" or "step-down".

b. The electrical energy was transferred from one circuit to another without any metallic connection being made between the two circuits, and from a direct current aspect the circuits are separate units.

c. The transformer in effect changed the nature of the connected load, or in other words changed the impedance of the load to a different value, excepting in the case of unity ratio.

In power work the principal use of a transformer is to accomplish the result given in **a** above, whereas in telephone work we are more directly concerned with **b** and **c**.

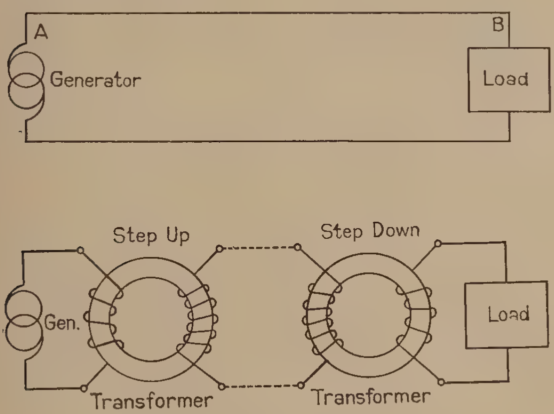



*Figure 216*

First, let us illustrate the power case by referring to Figure 216 which shows the use of transformers in a simple power transmission circuit. Let us assume that a 110-volt alternating current generator at station "A" is to be used to supply a load several miles away. The load is of such nature that it must have 100 amperes at an impressed voltage of 100 volts. Transmission from "A" to "B" must, therefore, be accomplished with a loss of 10 volts for a current of 100 amperes and this means that the RI drop of the line must not exceed 10 volts. Therefore, the resistance of the line from the equation

$$R = \frac{E}{I} = \frac{10}{100} = \frac{1}{10} \text{ ohm}$$

must not exceed 1/10th of an ohm, requiring extremely large copper conductors. If, however, a "step-up" transformer of 1-to-20 voltage ratio is inserted at the generator and a "step-down" transformer of 20-to-1 ratio is inserted at the load, from the relation between current, voltage, and power we shall find that the current in the transmission line will be equal to 5 amperes instead of 100 amperes and it will be possible to have a 200 volt drop in the line and still have a voltage of 2000 on the primary of the transformer at the distant end, or the required 100 volts when stepped down. Since the current in the line will now be 1/20th of 100, or 5 amperes, the resistance of the line in this case when calculated in the same way as before, gives—

$$R = \frac{200}{5} = 40 \text{ ohms}$$

We find, then, that the size of the conductors for the transmission line where the transformers are used must be such that the resistance will not exceed 40 ohms, whereas in the first case it must be such that the resistance will not exceed 1/10th ohm. The amount of copper required in the second case is the square of the transformer ratio which gives 1/400th or only 1/4th of one per cent. of that required in the first case. The economy due to the copper saving is apparent.

### 101. Transformer Applications to Telephone Circuits

The applications of transformers to telephone circuits are somewhat varied. The reduction of energy losses in alternating current transmission, as illustrated in Figure 216, has an application to telephone transmission but is not so important as other uses. The most general use is perhaps to accomplish the result given as **b** above, and inasmuch as the primary function of the coil is to transfer the energy to another circuit rather than to transform it to energy with different voltage and current characteristics, the designation "repeating coil" for the majority of types is more generally used in telephone work than the designation "transformer". In other words the primary function of the coil is to repeat the energy into a different circuit rather than transform it into a different state. There are, however, inequality ratio repeating coils which perform both functions, and in connection with telephone repeater circuits the input and output coils are used primarily to change the voltage and current characteristics of the energy and these are, accordingly, called "transformers" and not "repeating coils".

A further use is made of repeating coils to accomplish the results given as c above which in one sense are not different from those designated in **a** but from the telephone transmission aspect may be considered apart from energy transformation.

Although the specific applications of repeating coils and transformers are too numerous to be covered in a single Chapter, the more general ones may be mentioned. The first and most common one is in connection with the common battery cord circuit, as illustrated by Figure 217. Here the alternating current flow in one subscriber's line is

repeated into the other subscriber's line with little energy loss, and at the same time the split windings of the coils afford the proper direct current connections for each subscriber's station to receive a superposed D.C. current for transmitter supply. A similar use of the same coil is in connection with the trunk circuit, and this use was illustrated by Figure 168. Here only one side of the coil is used

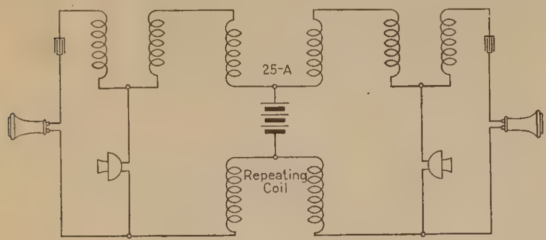



*Figure 217*

for battery supply while on the other side there is a condenser bridged at the midpoint of the winding, thereby prohibiting the flow of direct current from that side of the circuit. Here again the repeating coil accomplishes the transmission of voice current from one side to the other without being appreci-

40-ohm non-inductive windings (coded 25-S) is used in non-loaded 48-volt switching trunks. Coils of similar design but with inequality ratios, such as the 25-M, 25-N and 25-P, are used in connection with **loaded** switching trunks.

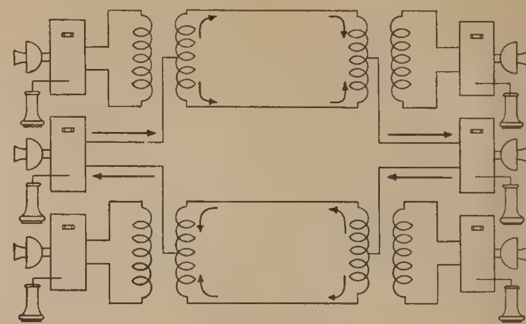


*Figure 219*

The next most general use of repeating coils in the telephone plant is in connection with phantom circuit operation, and inasmuch as we have not yet discussed the theory of the phantom, it will be taken up at this point.

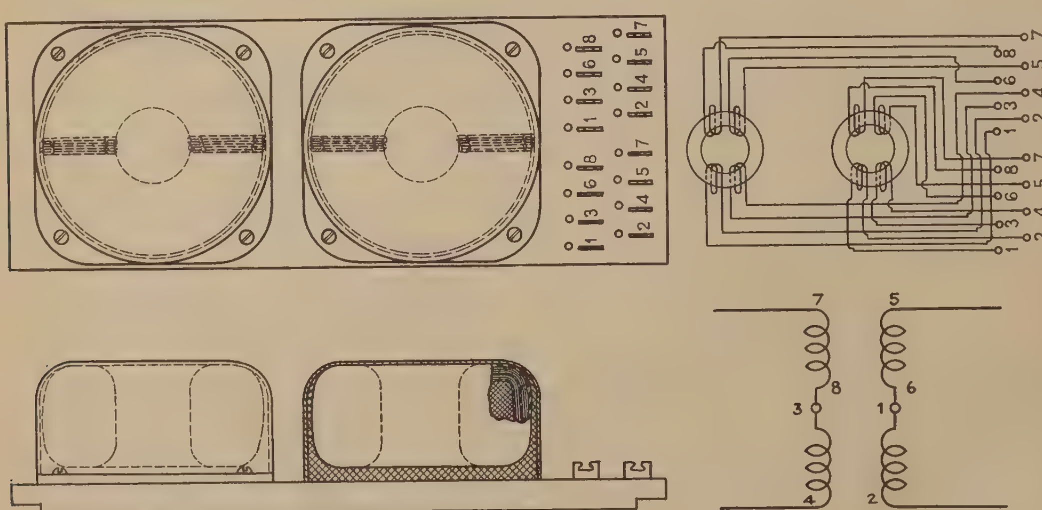



*Figure 218*

ably affected by the direct current features of the circuit.

The battery supply coil used in connection with the #1-D switchboard cord circuit at the A-board positions is coded #25-A. It has a 1-to-1 ratio and each of its four windings has 21 ohms resistance. The general appearance of this coil as well as the terminal designation and method of connecting in the circuit may be seen by referring to Figure 218. The same repeating coil is used in non-loaded, 24-volt switching trunks, and a similar coil with two

## 102. The Theory of the Phantom

Figure 219 gives a simplified diagram of two adjacent and similar telephone circuits arranged for phantom operation. It is possible by means of repeating coils installed at the terminals of these circuits to obtain a third telephone circuit. This third circuit is known as the "phantom" and utilizes the two conductors of each of the two principal, or "side" circuits, as one conductor of the third circuit. The two side circuits and the phantom circuit are together known as a "phantom group".

These three circuits employing only four line conductors can be used simultaneously without interference with each other, or without crosstalk between any combination, provided the four wires have identical electrical characteristics and are properly transposed to eliminate crosstalk.

The repeating coils required at the terminals are designed for voice current and ringing current frequencies, and do not appreciably impair transmission over the principal or side circuits. The third or phantom circuit is formed by connecting to the middle point of the line side of the repeating coil windings, as shown in the figure. Since the two wires of each side circuit are identical any current set up in the phantom circuit will divide equally at the midpoint of the repeating coil line windings. One part of the current will flow through one-half of the line winding, and the other part of the current will flow in the opposite direction through the other half of the line winding. The inductive effects will be neutralized, and there will be no resultant current set up in the drop or switchboard side of the repeating coil. Since the phantom current divides into two equal parts, the halves will flow in the same direction through the respective conductors of one side circuit and likewise return in the other side circuit. At any one point along a side circuit there will be no difference of potential between the two wires due to current in the phantom circuit and a telephone bridged across them will not detect the phantom conversation.

Since there is no connection, inductive or otherwise, between the two circuits at the terminals, it is equally true that a conversation over a side circuit cannot be heard in the phantom. This can be understood by imagining a flow in the closed side circuit through the line wires and the windings of the repeating coils at each end. With the side circuit conductors electrically equal there can be no difference of potential between the midpoint of the repeating coil line winding at one end and the midpoint of the repeating coil line winding at the other end because the drops of potential for the two parts of the side circuit are equal and opposite. If the side circuit, therefore, impresses no difference of potential on any part of the phantom circuit, the side circuit conversation cannot be heard over the phantom.

In the theory of the phantom it should not be forgotten that the conductors are assumed to be electrically identical, or in other words the conductors are perfectly balanced. The phantom is very sensitive to the slightest upset of this balance, and circuits that are sufficiently balanced to prevent objectionable crosstalk or noise in physical circuit operation may not be sufficiently balanced for successful phantom operation.

For coil rack mounting, the types of repeating coils now standard for phantom sets are of the same size and are similar in their external appearance to that illustrated in Figure 218. Two coils are mounted on one base, one coil being used for each side circuit; where the side circuits of the phantom group are used for telephone repeater operation, the rear coil is ordinarily used as a "balancing coil for the network". With this arrangement two adjacent front coils at the coil mounting rack are wired as one phantom set. Another standard type of coil is arranged for relay rack mounting and is different in appearance although having the same electrical characteristics. For both general types the coils are so wound that the windings 4-3 and 8-7, which form the line side of the coil, are well balanced so as to prevent the phantom current from crosstalking into the side circuit due to imperfections in the coil. The windings 2-1 and 6-5 are not so well balanced and should, therefore, always be connected as the drop.

The code numbers and electrical characteristics of several standard phantom coils are given by Table XI. In the manufacture of the No. 75 type coils a core made of many turns of fine gauged silicon steel wire is sawed so as to introduce a gap in the magnetic circuit. This gap is filled with a compressed powdered magnetic material, which while increasing slightly the core's reluctance, gives it a high degree of magnetic stability preventing permanent magnetization under abnormal service conditions. The two windings for the line side are wound on the core together to give the required high degree of balance but the drop windings are wound individually. The iron core of the coil is wrapped with cotton tape to protect the windings, and after the windings are put in place the coil itself is given a wrapping of cotton tape. It is then impregnated with a moisture proof compound, placed in its iron case, and melted resin is poured around it until it is firmly imbedded. The leads are then brought out to terminal punchings mounted on a wooden base.

The No. 85 and 62 type coils, arranged for coil and relay rack mounting respectively, are made in the same ratios as the No. 75 type coils and have approximately the same electrical characteristics. Their cores are made in the same way as those of the 75 type described above, except that the gap in the magnetic circuit is not filled with compressed iron powder. This feature makes these types of coils somewhat more stable and they are therefore especially well adapted for use in circuits on which rapidly changing direct currents are superposed, such as those involved in high speed telephone typewriter service. The same feature, however, tends to make these coils very inefficient at low frequencies and they cannot be used on circuits employing 20-cycle signalling.

**103. Autotransformers**

There is one type of transformer in which we are interested that may "step-up" or "step-down" the voltage, but does not employ a secondary circuit which is electrically separated from the primary circuit. It is called the "autotransformer", and the manner in which the primary and secondary windings are connected together electrically as well as

| TABLE XI PHANTOM SET REPEATING COILS | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Code Number | Coils per Base | Impedance Ratio Line to Drop 4-3 & 8-7 to 2-1 & 6-5 | D. C. Resistance Each Winding | | T—Network Values* (f = 1000) | | | | | |
| | | | 4-3 or 8-7 | 2-1 or 6-5 | a (Line) | | b (Drop) | | c | |
| | | | | | R | X | R | X | R | X |
| 75-A | 2 | 1 : 1 | 23.5 | 22 | 50.5 | +55.4 | 50.5 | +55.4 | 2208 | +18,250 |
| 75-B | 2 | 1 : 1.62 | 14.5 | 22 | –342. | –3080. | 522.5 | 3975. | 1736 | 14,330 |
| 75-C | 2 | 1.62 : 1 | 23.5 | 13.5 | 522.5 | 3975. | –342. | –3080. | 1736 | 14,330 |
| 75-D | 2 | 1 : 2.66 | 9.0 | 22 | –506. | –4300. | 903.5 | +7115. | 1355 | 11,190 |
| 75-E | 2 | 2.66 : 1 | 23.5 | 8.5 | 903.5 | 7115. | –506. | –4300. | 1355 | 11,190 |
| 76-A | 2 | 1 : 1 | 21. | 20 | 46.5 | 47.0 | 46.5 | 47.0 | 2096 | 17,625 |
| 77-A | 1 | 1 : 1 | 21. | 20 | 50.5 | 55.4 | 50.5 | 55.4 | 2208 | 18,250 |
| 78-A | 1 | 1 : 1 | 21. | 20 | 46.5 | 47.0 | 46.5 | 47.0 | 2096 | 17,625 |
| 25-A | 2 | 1 : 1 | 21. | 21 | 45.3 | 40. | 45.3 | 40. | 360 | 3,500 |

*Values given are for coils which have not been subjected to D. C. magnetizing currents.

magnetically is shown in Figure 220-A. As in any other transformer the primary and secondary windings are both wound on the same iron core so that any lines of force that thread one winding also thread the other. The fact that the windings are connected together does not prevent the voltages on the primary and secondary sides from being directly proportional to the number of turns in the windings just as in the regular transformer. Thus,

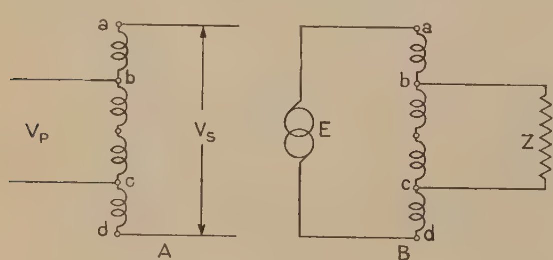



*Figure 220*

in Figure 220-A if there are 800 turns between **a** and **d**, 200 turns between **b** and **c**, and 110 volts are connected to **bc**, the primary, then the secondary voltage will be—

$$110 \times \frac{800}{200} = 440 \text{ volts}$$

This gives a one-to-four "step-up" transformer, and if we should reverse the primary and secondary connections we would have a four-to-one "step-down" transformer.

Figure 220-B shows a "step-down" autotransformer with a voltage E connected to its primary and a load of impedance Z connected to its secondary. Since the winding **bc** is shunted by the load Z, it will be apparent that only part of the current in Z will flow through the secondary winding, the remainder flowing through the portion of the primary winding represented by ab and cd, and the generator. In other words, the primary current will flow through only a portion of the primary winding and only a portion of the load current will flow through the secondary winding. In an ordinary transformer having entirely separate primary and secondary windings, on the other hand, all of the load current flows in the secondary winding, and all of the primary current flows in the primary winding only. In any case, in a practical transformer the currents cause $RI^2$ losses in the windings in which they flow. But because of the fact noted above, the $RI^2$ losses in the autotransformer are lower than in a transformer of the usual type, it being understood that the same size wire is used on each. Or in other words, an autotransformer can be designed to have the same losses as a regular transformer, and still have less copper in the windings, thereby effecting a saving.

An indication of the saving effected is given by the relation between currents in autotransformer windings, viz.,

$$\frac{I_{ad} \text{ (current in windings ab and cd)}}{I_{bc} \text{ (current in windings bc)}} = \frac{N_{bc} \text{ (no. of turns in winding bc)}}{N_{ad} \text{ (no. of turns in winding ad)}}$$

It will be noted that this relationship is similar to that given for the regular transformer, i.e., the currents are inversely proportional to the number of turns. As may be deduced from the discussion on losses, the autotransformer by reason of the smaller amount of copper needed for its construction is

cheaper than a regular transformer of the same load capacity; that is its sole advantage for power work. The electrical connection between windings, on the other hand, is a disadvantage in power work since it introduces the hazardous possibility of obtaining the full primary voltage on the load side of the device if, for example, the secondary winding should become open.

In telephone work we may occasionally wish to use a transformer to change the effective impedance of the circuit without changing the circuit continuity for telegraph currents, D.C. signalling or D.C. testing. Figure 221 shows how this is accomplished through the use of an autotransformer; the condenser connected between the windings prevents any direct current flow from one side of the circuit to the other.

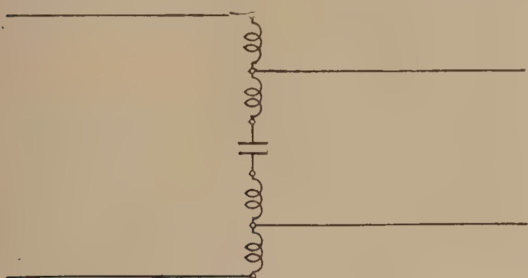


*Figure 221*

**104. The Bridge Type of Transformer**

In telephone repeater operation, as in duplex telegraphy, we must receive incoming energy and direct it into a receiving circuit (input) which is

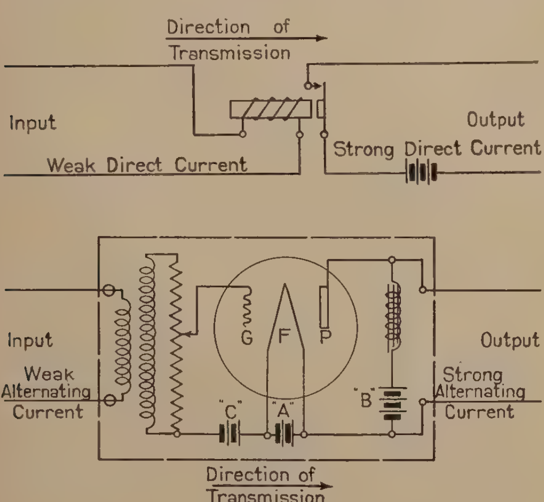



*Figure 222*

separate and distinct from the sending (output) circuit. This is essential inasmuch as the device used for amplifying voice frequency currents can amplify in one direction only. Its limitations in this respect are analogous to the relay which repeats a direct current signal from a circuit having a small amount of energy into one having a greater amount of energy. (See Figure 222). The use of such one-way amplifiers without some device for securing transmission in both directions would be restricted to such a layout as is shown in Figure 223 which would require not only twice the circuit facilities for each long distance connection, but also special telephones at each terminal. (Compare Figure 223 with Figure 121). We learned in Chapter XII how duplex telegraphy was accomplished over a single wire by application of the

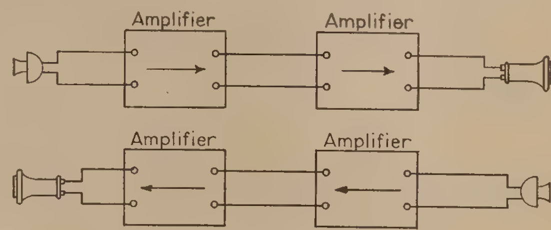



*Figure 223*

Wheatstone bridge principle and the use of an artificial line. The problem that confronted the Bell System engineers in the case of the telephone repeater was a great deal more complicated, but its solution was effected by employing the principle of bridge balance, using an artificial line called a "balancing network".

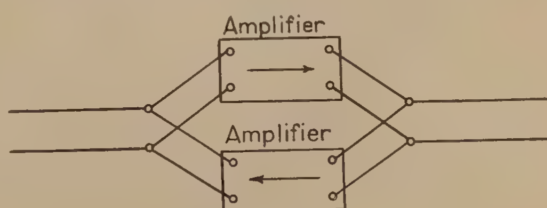



*Figure 224*

In the Chapter that is to follow we shall discuss the vacuum tube and its application in the telephone repeater. We wish to discuss at this time the "bridge transformer" which made two-way transmission over circuits with one-way amplifying devices possible. For this discussion we will consider the amplifier circuit as a device which amplifies the energy of the voice current connected to its input many times and delivers this energy without appreciable distortion to the output. It would not be possible for two such devices to be connected at the same point in a telephone circuit as shown in Figure 224, because any energy amplified in one circuit would be connected to the input of the other, to be again amplified and returned to the first. This returning energy would again reach the input of the first amplifier and this cycle would be repeated with energy thus circulating through the

two amplifiers and increasing in value until the condition of saturation was reached. The repeater would then continue to "howl" or "sing" indefinitely, rendering the telephone circuit inoperative.

To eliminate the possibility of "repeater singing" we must convert the ordinary telephone circuit into a "receiving" and a "sending" circuit which are independent of each other, i.e., as in the case of the duplex set the two circuits must be connected to the same line, yet any current flowing in one must not in any way affect the other. Evidently, we can obtain the desired result by applying the principle of Wheatstone bridge balance but the application is now to alternating currents. A Wheatstone bridge with proper modifications, however, can be operated

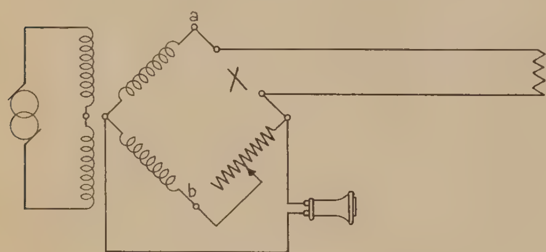



*Figure 225*

with alternating current as well as direct current. To illustrate, in Figure 225 we have a phantom repeating coil connected as an alternating current Wheatstone bridge with a few simple changes. Here the source of voltage is an A.C. generator instead of a battery, and instead of connecting the voltage to the points **a** and **b** as is usually done, the same results are accomplished by connecting it to the drop winding of the coil. The E.M.F. is then impressed across **a** and **b** by mutual induction instead of by direct connection but the result is, of course, the same. Instead of using a direct deflecting galvanometer we have substituted a telephone receiver which for alternating current of the voice frequency range is even more sensitive than a galvanometer.

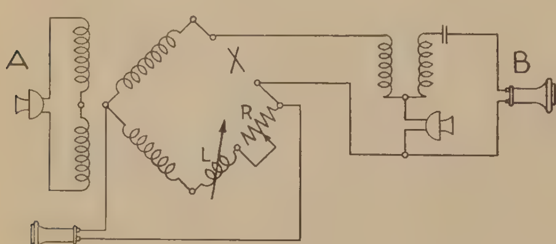



*Figure 226*

This circuit can now be used to measure the value of any resistance that may be connected to the "X" terminals; further, we can use this same circuit to measure any impedance that might be connected to the "X" terminals, provided the variable arm "R" has in series with it a variable reactance for balancing the reactive component of the unknown impedance.

Let us now assume that an alternating current bridge circuit, such as that shown in Figure 225 but arranged to measure impedance as well as non-inductive resistance, had a transmitter substituted for its A.C. generator and had a telephone line terminating in a subset at the distant end connected to the terminals "X". Such an arrangement is illustrated by Figure 226. Here we have a device for terminating an ordinary telephone circuit so as to provide a "receiving" and a "sending" circuit which are independent of each other. With the variable arm "Z" of the bridge adjusted to give perfect balance any voice current in the transmitter circuit at Station "A" cannot be heard in the receiver circuit at that station for the same reason that a galvanometer needle is stationary in any balanced bridge. We have "double tracked", so to speak, the ordinary two-way telephone circuit.

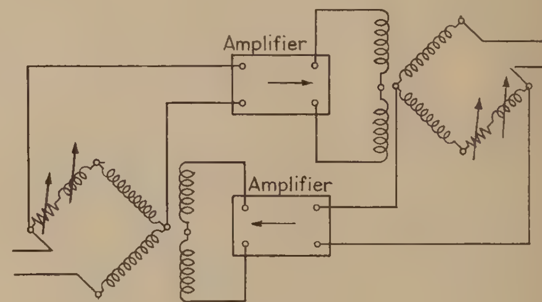



*Figure 227*

If we now take two such circuits, and introduce two amplifiers as shown in Figure 227, we have a device that may be used as a telephone repeater at some intermediate point in a telephone circuit. Here the energy coming from one repeater cannot find its way into the input of the other and cause "singing" as described in the foregoing.

The coil that takes the place of the bridge mechanism in Figure 226 and 227 is known as a "bridge transformer", sometimes called "hybrid transformer", "three winding transformer", "repeater output transformer", etc. In the actual coil, however, there are a few additional details of design that do not permit the identity of the simple A.C. bridge circuit to be so readily recognized. These are not difficult to follow, however, after having been once pointed out. In the first place the design shown in Figure 226 is not the conventional arrangement for illustrating the bridge transformer. The conventional schematic way of representing such a type transformer is shown in Figure 228, which it will be observed shows the same circuit connections as Figure 226 but is less similar to the convention for the Wheatstone bridge. In the actual bridge transformer the line coils are divided and connected on both sides of the line as

shown by Figure 229, in order that perfect symmetry in the wiring of the talking circuit may be maintained in the office cabling, thereby reducing any noise and crosstalk effects. Both sets of windings are inductively coupled to the external winding and the wire connection is such that this inductive relationship is maintained. Figure 230 shows the revised schematic of the amplifier connections

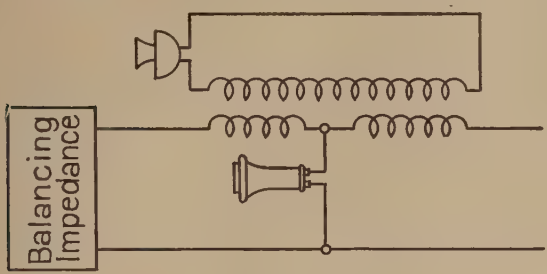



*Figure 228*

to two bridge transformers in a two-element, two-way telephone repeater circuit. There are other ways of connecting together the windings of the bridge transformer and of connecting the transformer into the telephone repeater circuit but in all cases the principle of operation is the same.

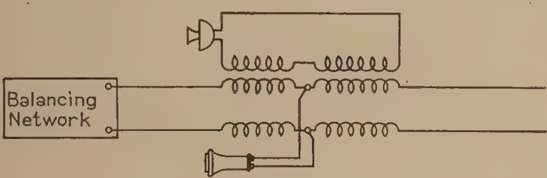



*Figure 229*

In the bridge transformer, as in other transformers or repeating coils, the design must be such as to give the desired impedance relations. Now, although a simple inequality ratio repeating coil must provide for connecting together two unequal

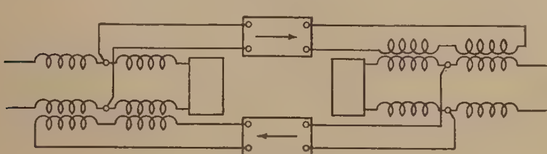


*Figure 230*

impedances, the bridge transformer must provide for matching four impedances. This is illustrated by Figure 231, where for convenience the coil is shown as in Figure 228 instead of as in Figure 229.

If $Z_1$ is the impedance of the telephone line and $Z_2$ the impedance of the balancing-network, $Z_1$ is, of course, equal to $Z_2$. In order to determine the relationships between $Z_3$ and $Z_4$ which represent the impedance of one amplifier input and the impedance of the other amplifier output, respectively, we shall analyze the electrical conditions. If we represent the source of voltage in the output circuit by a generator connected in series with $Z_4$, the energy supplied to the coil will divide equally at the bridge, one-half going to each of the two equal impedances, $Z_1$ and $Z_2$. The part going to $Z_2$, which represents the impedance of the network circuit, accomplishes no useful purpose and is lost. For this reason alone the amplifier must be adjusted to supply twice the energy that is required for actual transmission.

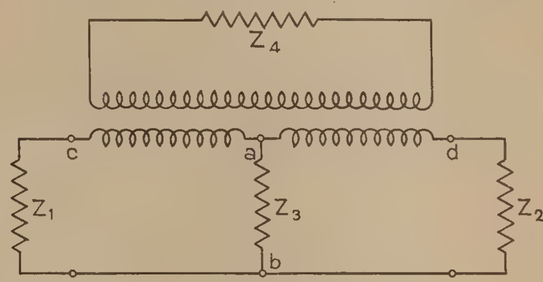



*Figure 231*

If, now, we simulate the conditions for inward transmission, connecting the generator in series with $Z_1$, the coil relations are such that half the energy is dissipated in $Z_4$ but none reaches $Z_2$. The voltage induced between **c** and **a** is equal to the voltage induced between **a** and **d** because the windings have the same number of turns and are on the same magnetic core. The turn ratio of the coil is fixed at such a value that the voltage induced in this winding is just equal to the voltage drop across $Z_3$ when it is traversed by a current. Consequently, points **b** and **d** are at the same potential. Accordingly, there will be no current flow between these points and $Z_2$ will consume no energy. On the other hand, half the incoming energy is lost in the impedance $Z_4$ so the amplifier must be further adjusted to compensate for this additional loss.

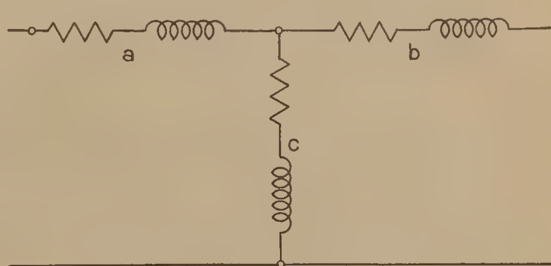



*Figure 232*

### 105. The Equivalent T-Network of a Transformer

In preceding Chapters where we learned to calculate the current values in any branch of a complicated alternating current network we dealt with only three physical circuit properties, namely, resistance, inductance, and capacity. In every case

these had some metallic connection. In this Chapter, however, we have found that any load that may be connected to the secondary of a transformer will affect the current flow in the primary though there may be no metallic connection between the two parts of the circuit. We have thus learned of a fourth physical property a circuit may have due to the introduction of the transformer and have called this fourth property "mutual induction", but fortunately we have a method of dealing with circuits containing transformers whereby we may reduce the physical properties of each transformer to an equivalent simple network, called a T-network, having metallic connection from one side to the other and made up of three self-inductances instead of a combination of self-inductances and mutual inductances. Figure 232 illustrates such an equivalent T-network, and we may simplify any complicated alternating current circuit containing transformers by substituting the equivalent T-network at the particular frequency for each transformer. The impedance values to be used in the equivalent networks are given in Table XI for the repeating coils there listed. It will be noted that in the case of the inequality ratio coils one of the T-arms has a negative value of impedance. It would be impossible, therefore, to actually construct such a T-network, but this does not in any way decrease the value of this device insofar as theoretical considerations and actual current or voltage calculations are concerned.

CHAPTER XVIII

# THE VACUUM TUBE AND A FEW OF ITS APPLICATIONS

## 106. Theory of the Vacuum Tube

The vacuum tube has become so generally known in connection with the radio receiving set that it needs no introduction as a "unique electrical device", but on the other hand the fundamental theory of its operation is not so simple as to be universally understood. The action of the vacuum tube is in one sense illusionary—it seems to contradict our more elementary understanding of circuits in that current actually flows through an open space with no accompanying arc or high voltage such as we naturally associate with a current flowing across an apparent "open". In the tube the current flow that takes place is from one electrode to another through a vacuum, and the conditions are such as to permit this flow without the use of extremely high potentials.

Any fundamental conception of the tube's action is based on the "electron theory" which we have discussed in Chapter I. But we have not heretofore dealt with the passage of electrons from one conducting substance to another, unless the two substances were actually in contact. Even in the case of the arc, the air or surrounding gas becomes a conductor. Yet, it is possible under a certain combination of physical conditions for electrons to pass from a conductor into the surrounding space. These conditions are as follows:

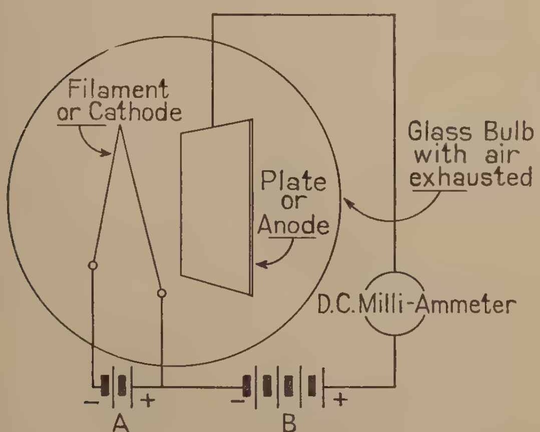



*Fig. 233—Two-Electrode Vacuum Tube.*

a. The metal which emits the electrons must have a high temperature (or be acted upon by some form of radiant energy).

b. Practically all air or other surrounding insulating material must be removed from contact with the metal.

c. There must exist some considerable force which overcomes the atom's attraction for the electron; for example, a positively charged plate brought near the substance from which the electrons are emitted will produce this force.

d. Surface conditions of the substance from which the electrons are emitted should be favorable to the action; for example, a chemical composition at the surface may have some influence, and coatings with chemical substances that emit electrons most freely are sometimes used to increase the activity.

Perhaps the simplest form of device for the flow of a stream of electrons through open space is the two-electrode vacuum tube illustrated in Figure 233. This figure shows a glass bulb containing two electrodes, one in the form of a metallic filament called a cathode which is so treated as to be the "emitting" element, and the other a metallic plate called the anode. All air and other gases are removed from the tube and the cathode is heated

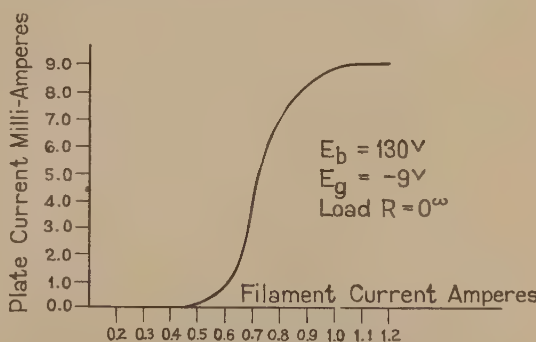



*Fig. 234—Plate Current—Filament Current Characteristic 101-D Tube.*

to a dull red glow. The most practical manner of heating this cathode is by a current of electricity from a relatively low voltage battery, such as "A". The cathode, of course, must be in the form of a metallic filament which readily permits heating by the flow of the current from the low voltage battery. Here it should be understood that the sole function of this battery, designated as "A", is to heat the cathode; certain secondary effects which may be traced to this battery will be explained later. Assuming that the filament is either of the proper chemical substance, or is coated with some chemical substance which will readily permit the emission of electrons, we have provided all conditions necessary for electron flow with the exception of "c" above. If now, a battery is connected between the filament (or cathode) and the metallic plate (or anode) and is so poled as to give

the anode a positive charge, this charge will exert a force of attraction on any electrons that may be emitted into the space surrounding the heated filament. Electrons escaping from the filament will be drawn to the plate by the force of attraction set up by its positive charge, and a continuous flow of electrons from filament to plate will result. The speed with which the electrons cross the gap is determined by the potential of the plate with respect to the filament.

This transfer of electrons is simply a flow of electrical current, and the battery B will sustain this flow in the same way that a battery sustains a flow when it is connected to any closed electrical circuit. With a milammeter connected as shown in Figure 233, the actual value of the current flowing under these conditions is indicated. We can change this current flow by changing the conditions which caused it. If we should insert a rheostat in series with the "A" battery so as to decrease the current in the filament, thereby lowering its temperature, we should find that the "space" current would also decrease and with the filament reduced to room temperature the milammeter would read zero, indicating zero space current. On the other hand, if we should increase the voltage of the "A" battery, thereby increasing the filament current and in turn increasing its temperature, the "space" current would be increased. This relation between filament current and space current for a typical vacuum tube is illustrated by the curve shown in Figure 234.

There is a limit, however, to the increase in temperature which gives an increase in the space current. This is due to the fact that electrons repel each other since they are all negatively charged, and free electrons in the space tend to keep new electrons from leaving the filament. In other words, the electrons themselves, when emitted, tend to counteract further emission of other electrons or exert a repelling force on electrons within the filament. This is called the "space charge effect". When the filament reaches a certain temperature there will be so many electrons in the space that their repelling effect prevents any further increase in the number leaving the filament. The space current then becomes constant regardless of further increase of temperature, and this accounts for the bending over of the curves in Figures 234 and 235. When conditions are as shown by point "A" in Figure 235, the tube is said to have reached the temperature saturation point and in practice this is the operating temperature for the filament since a slight change in the "A" battery voltage or current will not appreciably affect the tube's action.

Having disposed of the effects of changing the temperature of the filament, let us next consider the effects of a change in the voltage of the anode. We have said that the speed of the electron in proceeding from the filament to the plate depends upon the plate potential. We should, therefore, expect an increase in voltage to give two effects; first, the space current would be increased inasmuch as electrons are transferred more rapidly; second, since the number of electrons in the space surrounding the filament is reduced, the space charge effect will be lessened and the saturation point will be reached only at a higher temperature. The curves

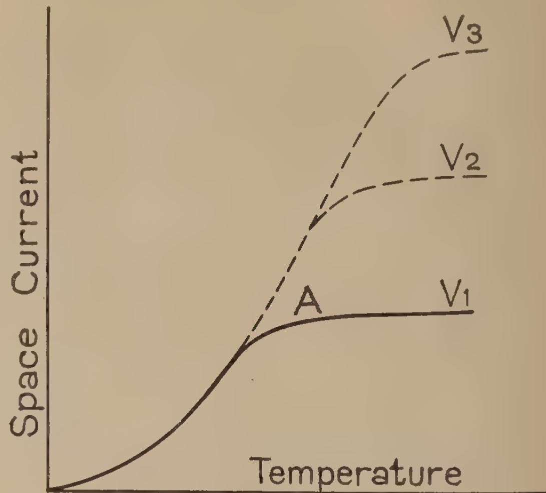


*Figure 235*

shown by Figure 235 illustrate such results — $V_1$, $V_2$, and $V_3$ represent three plate voltage values and it is seen that increasing the voltage increases the space current, extending the curve upward until a new temperature saturation point is reached. We

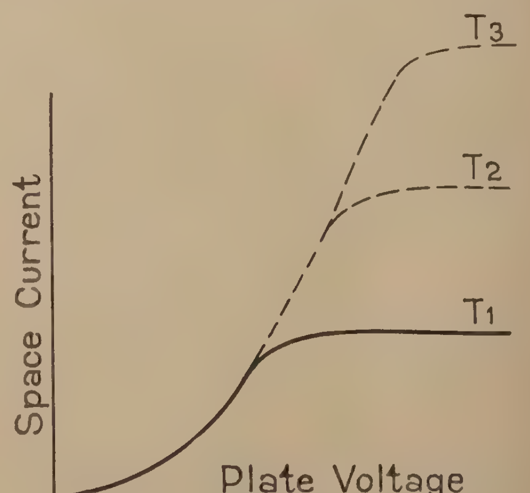


*Figure 236*

find, therefore, that the filament current which will give stable tube operation, i.e., the value giving saturation, depends on the plate voltage and any change in plate potential will affect the stability of

the tube unless a corresponding change is made in the filament current. There is always a limit, however, to the filament current that may be used inasmuch as the filament will either burn out or its life be greatly shortened if the current rises above a certain value.

In this connection let us refer to Figure 236. Here is a curve showing the relation between the space current and the plate voltage for three different values of filament temperature. We find that as the plate voltage is increased from zero, there is an increase in the space current until a saturation point for the given temperature is reached. The failure of the space current to continue its increase with increasing plate voltage is now due to the fact that the filament is emitting the maximum number of electrons possible for the particular temperature. If the filament temperature is increased, the voltage saturation point will increase correspondingly as shown by $T_2$ and $T_3$ in the figure. In practice, the vacuum tube is operated with a plate voltage well below the voltage saturation value.

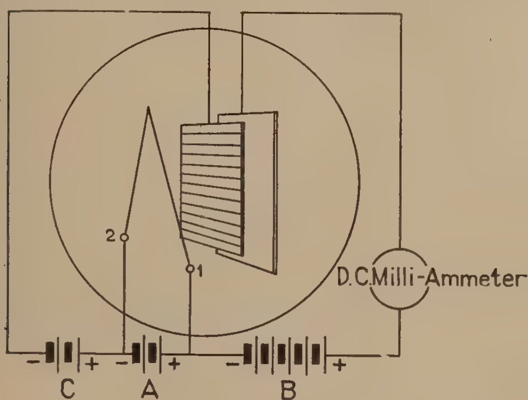



*Fig. 237—Three Electrode Vacuum Tube.*

The two-electrode vacuum tube is discussed here primarily as leading up to the theory of the three-electrode tube. It, however, has practical use to some extent in radio receiving, electrical measuring, etc., on account of its rectifying property, i.e., the space between the filament and the plate permits only a unidirectional flow of current. If an alternating E.M.F. is substituted for the battery B in Figure 233 we shall find a flow of space current varying in value for one-half cycle of voltage, but completely cut off for that half of the cycle which gives the plate a negative charge instead of a positive charge. This would give "pulses" of current flow always in the same direction. The original tube for such use was called the "Fleming" valve.

The type of vacuum tube which this Company employs in its telephone repeaters, radio apparatus and carrier systems differs from the two-electrode tube in that a third electrode or grid is interposed between the filament and the plate, as indicated in Figure 237. In this device the electrons which leave the filament must find their way around and between the bars of the grid to reach the plate. Their passage, therefore, is influenced by any force that may be set up by a charge on the grid. Due to the relative positions of the grid and plate with respect to the filament, a change of potential of the grid has a greater effect on the space current than an equal change in the potential of the plate; for example, a change of one volt in the potential of the grid of the 101-F vacuum tube used in telephone repeater circuits would require a change of approximately 6.6 volts in the plate potential to restore the original value of the space current. In other words, one volt potential impressed on the grid has the same effect as 6.6 volts acting in the plate circuit. The ratio of the voltage effect on the plate circuit to the change in grid potential producing an equivalent effect is called the "voltage amplifying factor" of the tube and is usually designated by the symbol "$\mu$". Its value depends entirely upon the mechanical design of the tube.

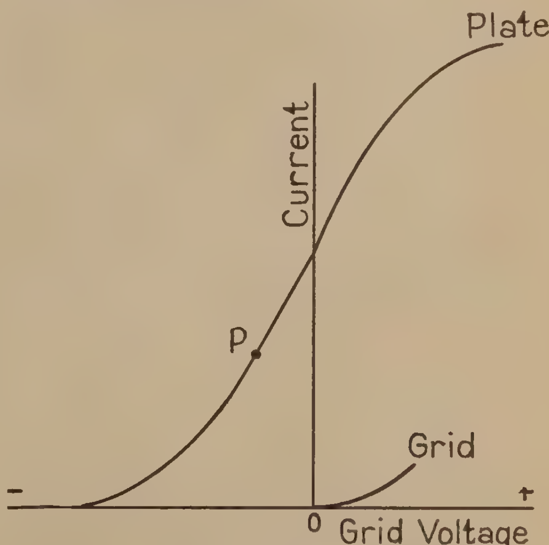



*Fig. 238—"Plate Current—Grid Voltage" Characteristic of Three—Electrode Vacuum Tube.*

The utility of the vacuum tube in communication circuits is for the most part due to the sensitive response in the plate circuit to small impressed potentials on the grid. In this connection the grid in its control over the flow of current in another circuit is analogous to the valve of the water faucet. It decreases or increases the flow of current in the plate circuit, and the force necessary to thus regulate the flow is independent of the value of current or the amount of energy that may exist in the plate circuit. To best illustrate the relation between the grid voltage and the current flow in the plate circuit a curve is employed which is known as the characteristic operating curve of the particular type of tube. Figure 238 illustrates such a curve. Here any voltage that is impressed on the grid, either positive or negative, is laid off to the right

or left of the zero point, respectively, and the vertical ordinate intersects the curve at the plate current value.

Starting with the grid strongly negative with respect to the filament, its field will overpower that due to the plate and electrons will not be permitted to leave the filament; i.e., the space current will be zero. If, now, the grid is gradually charged in the positive direction, a point will be reached at which the effect of the grid no longer overpowers that of the plate and a small current flows. No current reaches the grid, which is still negative with reference to the filament and therefore repels the electrons. The plate current rises according to the upper curve of Figure 238. When the grid becomes positive with respect to the filament it draws some of the electrons to itself, establishing a grid current which varies as shown by the lower curve. The sum of the grid and plate currents is limited by the ability of the filament to emit the necessary number of electrons; consequently, as the grid becomes more and more positive, the plate current curve will bend toward a horizontal direction at its upper end and may even fall again due to the grid taking a larger share of the electrons. The point at which this flattening takes place depends on the temperature of the filament, as pointed out in connection with Figure 236. As previously noted, repeater vacuum tubes are usually so worked that the limiting effects of filament emission are not encountered, but when the activity of the filament, i.e., its ability to emit electrons is reduced through age or low filament current, the effect is manifested by reduced space current.

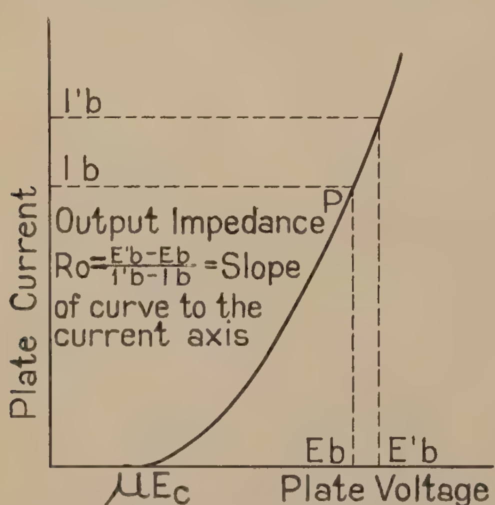



*Fig. 239—"Plate Current—Plate Voltage" Characteristic of Three—Electrode Vacuum Tube.*

The circuit between the grid and filament is substantially open at telephone frequencies when the grid is negative since no current flows through the space by transfer of electrons, but a very small charging current flows due to the electrostatic capacity between these electrodes. At telephonic frequencies this current is usually negligible, but at high frequencies, such as are encountered in radio work, this capacity effect becomes important.

When the grid has a negative potential and the plate voltage is varied, the space current curve differs from that shown in Figure 236 in that the potential of the plate must be made great enough to overcome the effect of the grid before any current will flow. This is illustrated by Figure 239. The potential at which current begins to flow is $\mu E_c$ where $E_c$ is the voltage of the grid or "C" battery. Above this value the current varies as shown by the curve in Figure 239 which is similar to the curve given by a two-electrode tube. Some point P on this curve corresponds to the working plate voltage $E_b$ as determined by the plate battery. The corresponding space current is $I_b$. The direct current resistance, i.e., the resistance that the tube offers to the direct current from the battery, is given by the expression

$$\text{Rd. c.} = \frac{E_b}{I_b} \qquad (70)$$

which is the ordinary form of Ohm's law. It should be remembered that $R_{d.\,c.}$ is not constant but varies with both grid and plate voltages.

The alternating current output resistance of the tube is quite different from this direct current resistance and should not be confused with it. The alternating output voltage and current are superimposed on the direct plate voltages and current referred to above. Imagine that the plate voltage (Figure 239) is changed somewhat to a new value $E_b'$. The plate current will change to a new value $I_b'$. The alternating current output impedance is the ratio of the added voltage to the increase of current, i.e.:

$$\text{Output impedance} = \frac{E_b' - E_b}{I_b' - I_b} \qquad (71)$$

From this it can readily be seen that the output impedance depends on the slope of the "plate voltage—plate current" curve with respect to the current axis. As the plate voltage rises, the curve becomes more nearly parallel to the current axis and the impedance falls. A fall of plate voltage is accompanied by a rise of impedance. It can be shown that the impedance is inversely proportional to the quantity $\sqrt{E_b + \mu E_c}$ ($E_c$ is usually negative so the quantity under the radical is less than $E_b$). From this fact and the value of the impedance under standard conditions, the value of the output impedance for any values of $E_b$ and $E_c$ may be estimated. The output impedance can also be found from the grid voltage-plate current curve of Figure 238 by taking the slope at the point P corresponding to the steady grid potential with respect to the current axis, and multiplying this by $\mu$, because a change in the grid potential has the same

effect as a change μ times as great in the plate voltage.

In the foregoing the alternating current resistance of the "space" and the output impedance of the tube are considered the same since the impedance does not contain a reactive component. This is permissible, of course, if we ignore the capacity between the plate and the grid, which like the capacity between the filament and grid is negligible at telephone frequencies.

### 107. Characteristics of Various Types of Vacuum Tubes

Commercially there are many types of vacuum tubes designed for various uses, depending on quantities of energy to be handled, amount of amplification desired in a single stage, whether used exclusively for amplification or both amplification and rectification, voltage and types of battery supply available for the various battery connections, etc.

Table XII and Figure 240 give the electrical characteristics of most of the types of tubes that may be encountered in the telephone plant.

TABLE XII

ELECTRICAL CONSTANTS FOR VARIOUS TYPES OF VACUUM TUBES

| Code No. | Uses | Current and Voltage Values | | | | | μ | $R_o$ (Ohms) | Gain TU | Power Output Watts | Max. Safe $E_b$ | Hrs. Ave. Life |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_a$ (Amps) | $I_b$ (Mils) | $E_a$ | $E_b$ | $E_c$ | | | | | | |
| 101-F (L) | Modulator, Amplifier, Oscillator | .50 | 7. | 4.0 | +130 | —8. | 6.6 | 6000 | 30. | 0.6 | 160 | 25000 |
| 102-F (V) | Amplifier, Detector | .50 | .75 | 2.0 | +130 | —1.5 | 30. | 60000 | 33.5 | .0042 | 160 | 25000 |
| 104-D (O) | Amplifier | .97 | 20. | 4.4 | +130 | —22½ | 2.5 | 2300 | 26. | 0.17 | 160 | 10000 |
| 203-D (J) | Amplifier, Detector, Oscillator | 1.0 | 1.5 | 2.5 | +67½ | —9.5 | 6.5 | 12000 | 27. | .009 | 100 | 10000 |
| 205-D (E) | Amplifier, Oscillator, Modulator | 1.6 | 33. | 4.5 | +350 | —22½ | 7 | 3500 | 33. | 0.89 | 350 | 5000 |
| 215-A (N) | Amplifier, Detector, Oscillator | .25 | 1.0 | 1.0 | +67½ | —6.0 | 6.0 | 20000 | 24. | .008 | 100 | 2500 |

This brings us to the many actual uses that can be made of the vacuum tube on account of the singular manner in which it permits a small voltage value to control an appreciable current flow. In the first place, any use requires that the particular tube have associated with it the proper circuit for performing some useful function. The applications, therefore, involve circuit theory as well as an analysis of tube characteristics. Bearing this in mind let us now take up the more important applications for communication work.

These are as follows:

a. For amplifying alternating current energy without appreciable distortion in wave form.

b. As a rectifying device or as a detector.

c. As a generator for alternating currents of high frequency.

d. As a modulator, i.e., a device for "molding" the wave form of a high frequency alternating current so that it will carry, so to speak, the characteristics of a wave form of some other frequency, usually lower in value.

e. As a demodulator, i.e., a device for a process the reverse of "d" above.

While it is not the intent to discuss all the applications of the vacuum tube mentioned above in this Chapter, we shall take up those having the most direct bearing on the operation of telephone repeaters.

### 108. The Vacuum Tube as an Amplifier

We employ the vacuum tube as an amplifier in such devices as telephone repeaters, loud speaking

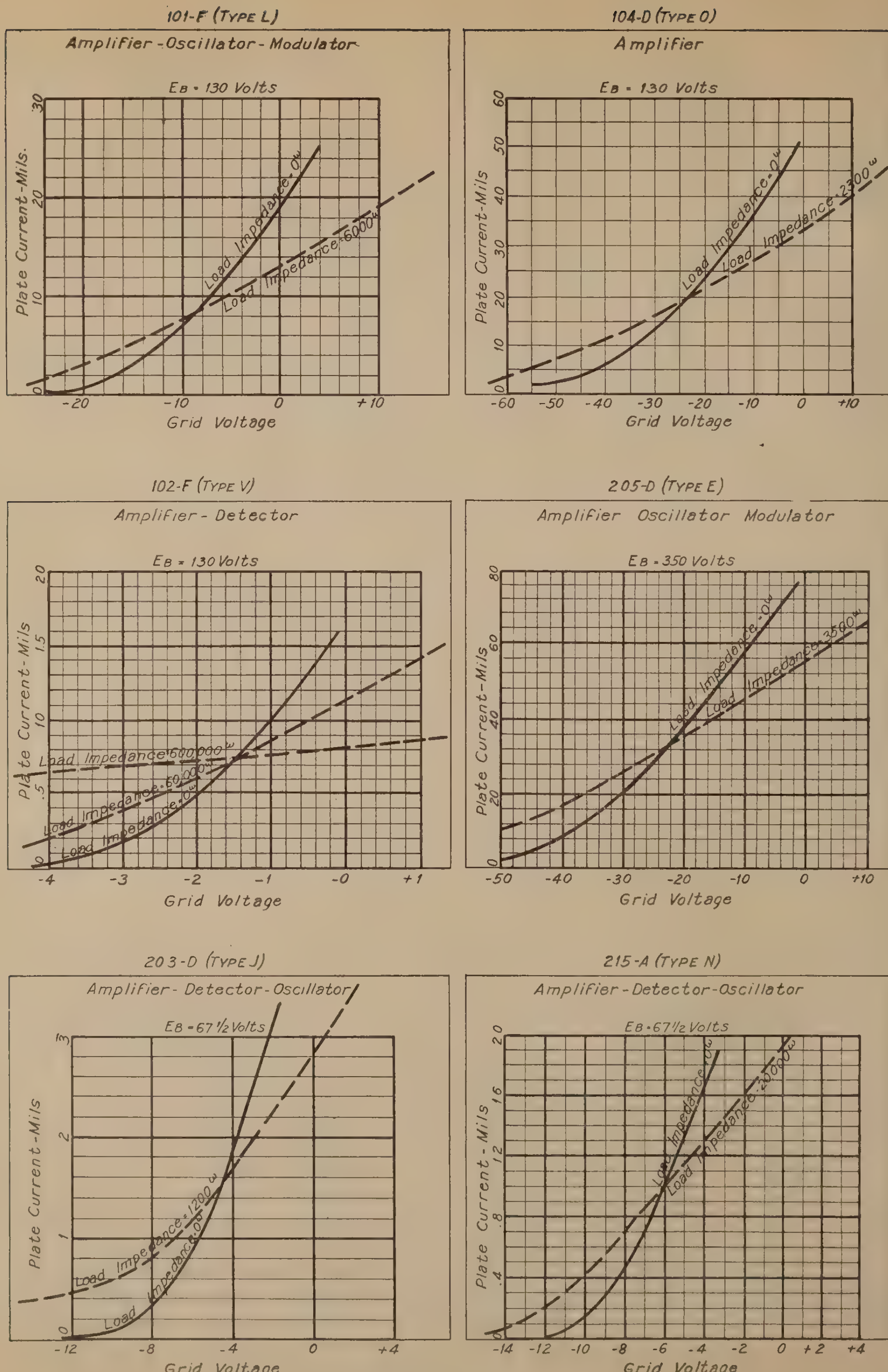



*Fig. 240—"$E_c$-$I_b$" Characteristic Curves of Various Types of Vacuum Tubes.*

telephones, extremely high impedance monitoring taps for service observation on long important toll connections, very sensitive high frequency measuring instruments for reading alternating current values used in communication work, etc. A typical

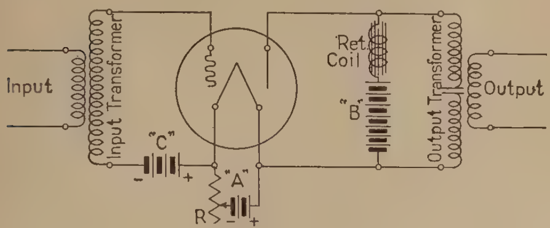



*Fig. 241—Simple Amplifying Circuit.*

circuit connection in its simplest form for a tube when so used is illustrated by Figure 241. Here we have on the left a circuit containing an alternating current of very low energy which is commonly called the "input" circuit. Let us assume that this energy is a very feeble voice current, and it is desired to amplify it many times and reproduce it without appreciable distortion in another circuit which is shown at the right of the figure and designated as an "output" circuit. Let us assume further that the operating characteristic curve for the vacuum tube shown in Figure 241 is that shown in Figure 242. The rheostat in series with the A battery is adjusted to such value as to give the proper filament current and one that will give high stability for the particular value of the battery B. In order to prevent the battery B from shunting the output circuit through the output transformer, we have inserted in series with this battery a retardation coil which permits the flow of direct current but greatly retards the flow of alternating current. In order that the current supplied to the plate by this battery will not be shunted by the primary winding of the output transformer, we have inserted a condenser in series with this winding.

Now, the potential that we are going to impress on the grid in Figure 241 will not be the steady one due entirely to the C battery, i.e., $E_c$, but it will be an alternating E.M.F. from the secondary of the input transformer superposed on the potential of the C battery. For one-half cycle this alternating E. M.F. will add to the voltage of the C battery and for the other half cycle it will subtract from the voltage of the C battery. We, therefore, have a varying grid potential due to the value $E_c$ plus an alternating potential, or we have what we may term a fluctuating potential with an instantaneous value that we shall represent by the symbol $e_c$. The value of the direct current component, $E_c$, can be adjusted to any value desired by increasing or decreasing the voltage of the C battery. The alternating component can be made very large compared to the potential of the circuit from which it was taken by designing the input transformer for a very high step-up ratio. This is feasible since the grid circuit under the conditions in the figure is practically open and no current flows in the secondary of the transformer, and, consequently, but very little current must flow in the primary of the transformer. Within the limitations of the transformer design, therefore, we can increase the alternating component of the voltage impressed across the grid to any desired value in spite of the fact that the energy in the input circuit is almost negligible. The reason for this is that we do not theoretically "draw from" this energy because if we did we should require grid current as well as grid voltage. But with no current, or with an open circuit, any value of voltage we might name would represent zero energy.

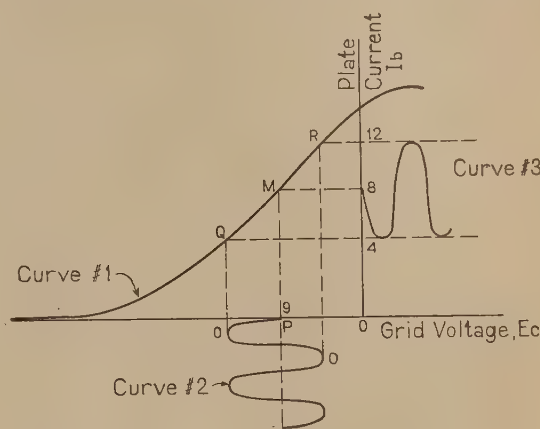



*Figure 242*

Referring again to Figure 242, let us assume that we have an appreciable alternating E.M.F. impressed on the grid which tends to increase and decrease the voltage of the grid alternately for each cycle. This we can represent by curve #2, which for convenience is charted downward. Now let us follow this curve beginning at the point "P". Here we have a grid E.M.F. created by the C battery alone which is nine volts in value and which adjusts the current flowing in the plate circuit to eight milamperes. This we find to be the case by projecting upward to the characteristic curve, point "M", and projecting across to the plate current scale. This means that with nine volts fixed grid potential we have eight milamperes fixed plate current, but now when the first half cycle of the alternating component beginning at point "P" and reaching a peak at point "O" is added to the C battery voltage and projected upward to the characteristic curve we have the point "Q" which corresponds to a plate current of four milamperes. Now, going from the point "O" to the point "O′", which is the peak of the other half cycle, and projecting from the point "O′" to the characteristic curve we have the point "R" which corresponds to 12 milamperes. The value of the plate current is, therefore, changing as determined by the factor $\mu e_c$, and we have in the plate circuit an alternating component of current in the same way that we have in the

grid circuit an alternating component of voltage impressed on the direct voltage of the battery C. In the plate circuit this alternating component of current is not permitted to flow through the battery on account of the retardation coil in series with the battery, but is forced to flow through the primary of the output transformer.

Referring again to our characteristic curve, if the portion of it between the points "Q" and "R" had been a straight line every point in curve #3 measured from a neutral axis would be proportional to corresponding points on curve #2 measured from its neutral axis, and we could say that curve #3 was identical in wave form to curve #2. To illustrate, if curve #2 were a sine wave, curve #3 would be a sine wave; if curve #2 were a complex wave representing some vowel of the voice, curve #3 would be a complex wave representing the same vowel of the voice.

In the above action we have accomplished considerable amplification of energy. The current flowing in the input circuit was very feeble, being merely that required to maintain magnetization of the transformer. In the output circuit, however, we had flowing a current of several milamperes, and therefore, accomplished this considerable amplification of the energy impressed on the input circuit. Further, the amplified energy had the same frequency and wave form as the input energy. Now the amount of amplification for a device of this kind depends on three factors; first, the slope of the straight line portion of the characteristic curve, or the constant of the tube, which is the same thing expressed in other terms; second, the voltage step-up ratio of the input transformer; and third, the losses in the circuit which must, of course, be subtracted.

There are a number of additional circuit features not shown in Figure 241 that are required to meet conditions in practice. Perhaps the most important of these is the arrangement for adjusting the amount of "gain", or amplification. There are four practical methods of doing this, one of which is to place some form of network in the output circuit to absorb the amplified energy. The other three are all schemes for regulating the potential impressed across the grid and these are the ones most generally used.

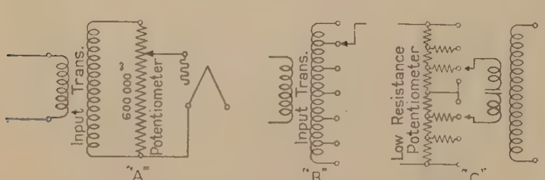



*Fig. 243—Methods of Adjusting Amplifier Gain.*

Figure 243 illustrates the three devices. Figure 243-A is the oldest scheme and employs a very high resistance potentiometer ($600{,}000\omega$) between the secondary winding of the input transformer and the grid. This, of course, draws a certain amount of current from the secondary of the transformer and consequently represents a certain amount of energy supplied to the input circuit. Later developments employ a transformer having numerous taps on the secondary winding. This arrangement is illustrated in Figure 243-B. There is also in very general use a gain regulating device which consists of a potentiometer on the primary side of the input coil, as represented by Figure 243-C. Here the potentiometer will have much lower resistance inasmuch as it is on the low side of the transformer. It requires duplicate contacts, however, in order not to throw an unbalance on the connecting line due to the lack of symmetry in the circuit. In order that the line may be properly terminated, this potentiometer has a resistance nearly equal to the characteristic impedance of the line.

Having a picture of the circumstances under which the tube operates in the ordinary circuit, we may now deal with certain adjustments that must be made in the values $E_b$ and $E_c$ and in the characteristic curve between these values, i.e., the "grid voltage-plate current" curve which we discussed in the previous articles and which is represented by Figure 238. In the first place, the battery A, although intended primarily to heat the filament, affects the values $E_b$ and $E_c$. This can be understood by referring again to Figure 237. Here we have represented the voltage between the plate and filament, $E_b$, by the battery B, but this E.M.F. is impressed between point "1" of the filament and the plate while the E.M.F. impressed between point "2" of the filament and the plate would be equal to the voltage of the battery B plus an $RI_a$ drop due to the current the battery A furnishes through the resistance of the filament. The average value, then, for $E_b$ would be the voltage between the plate and the middle of the filament which would be equal to the voltage of the battery B plus one-half of the $RI_a$ drop in the filament.

In the same way that the $RI_a$ drop may slightly affect the voltage of the B battery it may more appreciably affect the voltage of the C battery since the C battery is usually small. It should be remembered, therefore, that while the function of the A battery is primarily to heat the filament, it tends to increase the effective value of both the B and C batteries when connected as shown in Figure 237 and would decrease the effective values if connected with its polarity reversed. For economical reasons it should be always connected as shown, thereby permitting the use of B and C batteries of less voltage and consequently less expense. Ordinarily, in plotting characteristic curves of vacuum tubes it is understood that the A battery is poled so as to add to a negative grid and positive plate and the characteristic curves in this Chapter are plotted on that basis. This permits the use of actual voltage values as ordinates, etc., instead of corrected values.

Another very important consideration coming from the actual conditions under which the tube is

operated, is the effect of external plate circuit impedance on the "$E_c$ — $I_b$", or "grid voltage-plate current", characteristic curve. In Figure 237 there is no impedance in series with the B battery other than the resistance of the milammeter. In Figure 241 we show the primary of an output transformer bridging this circuit. If we should consider the plate circuit as a direct E.M.F. in series with a definite impedance, we would not expect the potential of the plate to remain constant when there was an alternating current component represented in the plate current, because this alternating current in flowing through the impedance would cause a drop which for the instant would seriously affect the plate voltage. It is, therefore, necessary to take this into consideration in the characteristic curve and in doing so the effect is a flattened curve as illustrated by Figure 244. The dotted curves in Figure 240 are corrected operating characteristics for external impedance conditions as given.

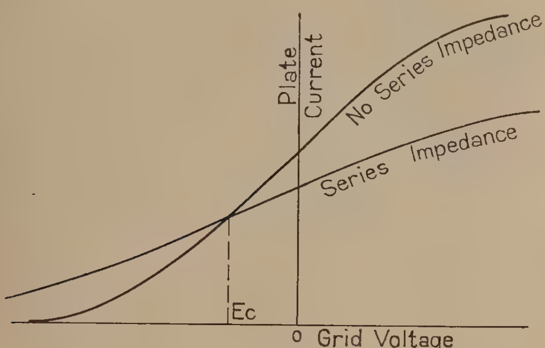



*Figure 244*

### 109. The Vacuum Tube as a Rectifying Device

We have explained that for amplification without distortion, the straight line portion of the characteristic curve must be employed as shown in Figure 242. If a curved portion of the curve were employed, distortion would result. Within certain limits this can be controlled by the C battery which in Figure 242 had a value of nine volts, and this was a case of the chosen value restricting the amplifying operation to the straight line portion of curve #1. Let us consider, on the other hand, an extreme case where C battery voltage is so great as to give practically zero plate current with no superposed alternating E.M.F. Such a condition is represented by the point "P" in Figure 245. If under this condition we superposed on the grid the same alternating potential as shown by curve #2 in Figure 242 we would get an entirely different result. During the first half cycle which reaches a peak at point "O" (Figure 245) there is no appreciable effect in the plate circuit as this half cycle projected on the operating curve falls on the zero line. The other half cycle, however, subtracts from the $E_c$ value and projects on a portion of the characteristic curve which has appreciable slope though somewhat curved. This establishes a plate current in the form of unidirectional pulses for each half cycle of the impressed E.M.F. which subtracts from the C battery voltage. The tube's response in this case is a rectifying action which is similar to that for which the two electrode tube is sometimes employed, but gives a certain amount of amplification at the same time, which is not given by the two electrode tube.

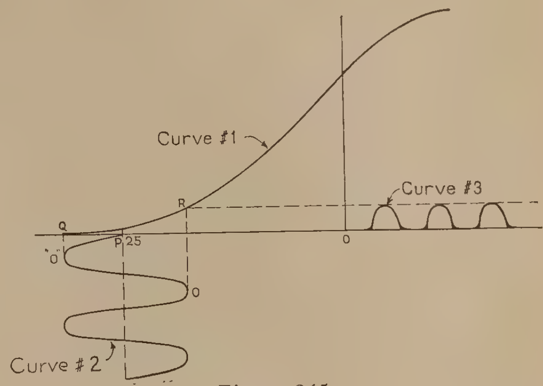



*Figure 245*

Although in Figure 245 we have chosen a value of $E_c$ that gives very nearly zero for the value $I_b$, there would be some rectifying effects on any curved portion of the characteristic curve. It is, therefore, important that operation for amplification be restricted to the straight line portion as any degree of rectification will distort the wave form and thereby impair voice current quality.

### 110. The Vacuum Tube as a Generator (Oscillator)

Any amplifying circuit can be used as an alternating current generator under the following conditions:

a. There must be some connection between the output and input circuit whereby a part of the output energy will be fed back into the input circuit.

b. The amount of energy that is fed back from the output to the input must be at least as great as the reciprocal of the energy amplification, e.g., if the circuit amplifies the energy 300 times, at least 1/3rd of one per cent., must be fed back into the input circuit.

c. Either the input or output circuit should have adjusted capacity and inductance to establish resonance, thereby determining the frequency generated.

d. The current coming from the output circuit and reaching the input circuit through the feed back connection should be "synchronized" (added in phase) to the existing current in the input circuit.

Figure 246 represents a modification of the amplifier circuit already discussed, for generating an alternating current. Here we can see that the amplification will be maintained indefinitely by input energy being fed back from the output circuit Such a circuit will gradually build up until the full capacity of the tube is reached. Under these conditions, however, the operation cannot be restricted to the straight portion of the curve and the wave form of the generated current will not be a pure sine wave but will contain harmonics. These are usually taken care of by filtering devices and by circuit modifications consisting of RI drops introduced at various places by the insertion of pure resistance. An alternating current generating device of this kind is called a "vacuum tube oscillator".

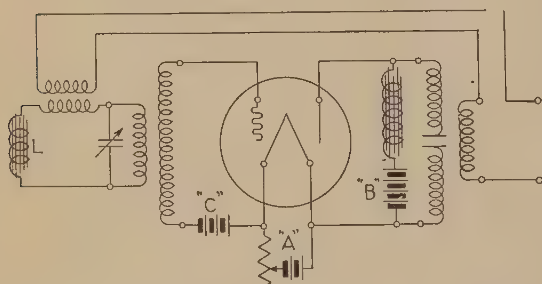



*Fig. 246—Principle of Vacuum Tube Oscillator.*

### 111. The Telephone Repeater

The mass of technical information concerning telephone repeater circuits as developed by the Bell System Engineers and employed in long distance transmission, is a complete study within itself and only the theory of the simplified telephone repeater circuit as a whole can be taken up here. In general, telephone repeater practices involve the following:

a. The use of one-way amplifier circuits designed to give the required amplification or transmission gain and equipped with regulating devices for adjusting the gain to meet operating conditions.

b. The use of the bridge type transformer for adapting one-way amplifiers to two-way transmission.

c. Providing the proper network balancing equipment for closely approximating the impedances of each line circuit and its associated apparatus to which the telephone repeater is connected, thereby maintaining the degree of balance required by the bridge transformer for its proper functioning. Here proper functioning means that energy at voice current frequencies from the output of one amplifier must be prevented from reaching the input of the other, which would cause impairment in the quality of transmission or even "singing" as was explained in Chapter XVII.

d. The use of filtering devices for eliminating altogether any energy not at the frequencies essential for the required quality in the voice transmission.

e. The use of miscellaneous apparatus and circuit features for adapting the telephone repeater circuit to the standard operating and Central Office practices.

One very common type of telephone repeater which perhaps best illustrates the circuit assembly

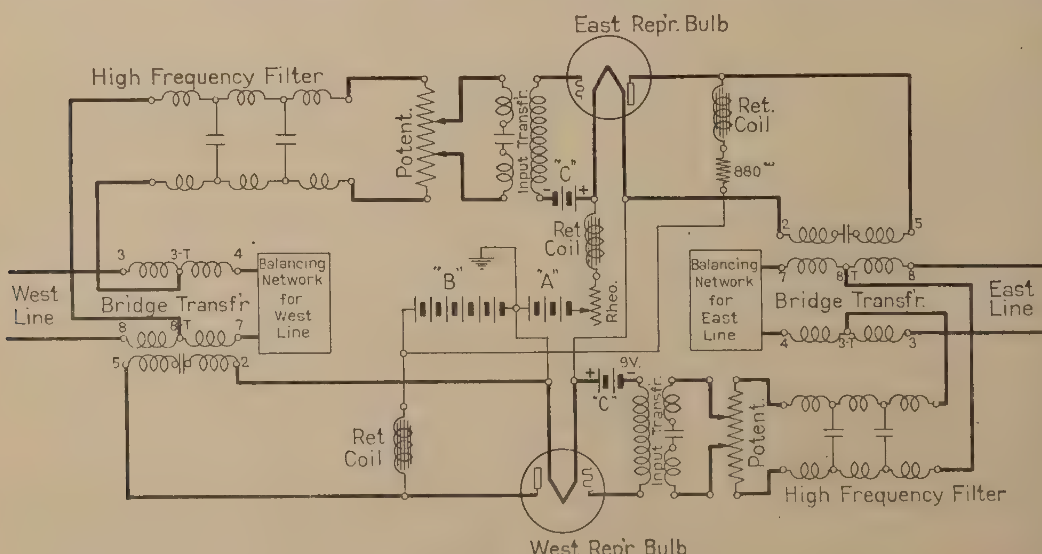
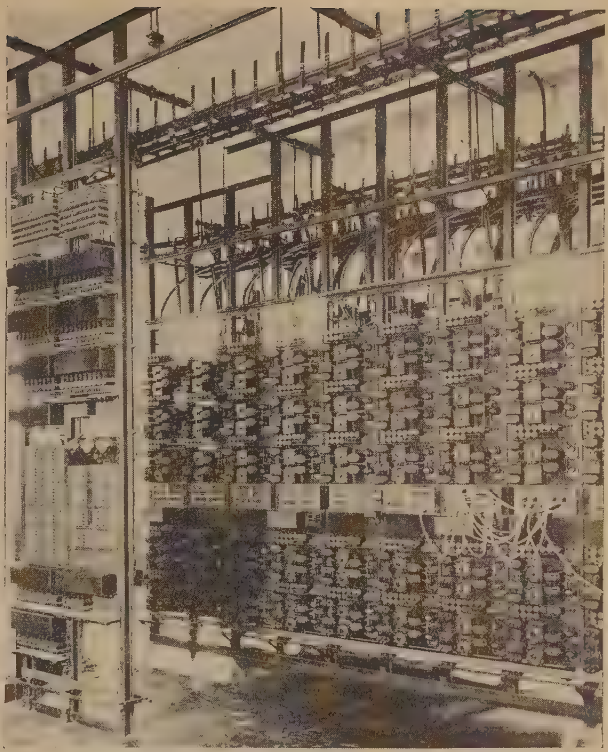
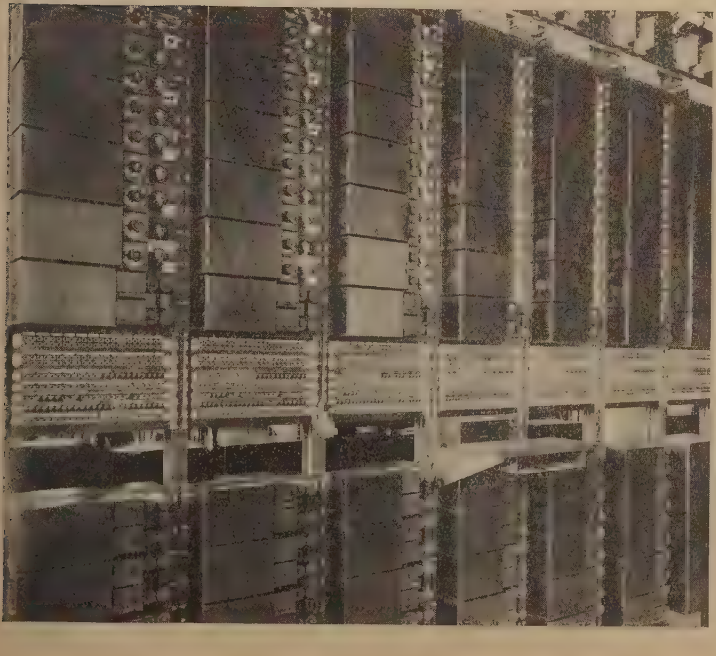


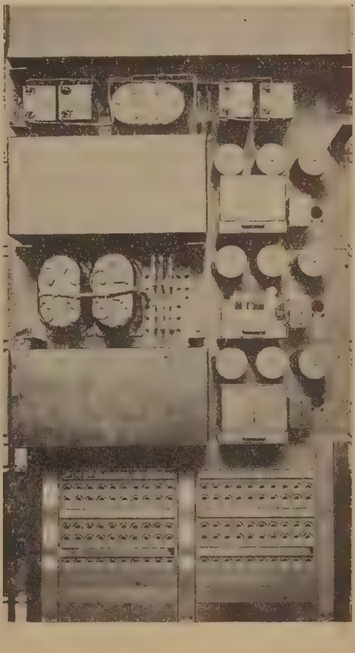

*Fig. 247—Simplified Circuit of 22-Type Telephone Repeater.*



Telephone Repeaters and Associated Apparatus

*Above left*—Bank of Reading type four-wire repeaters.
*Above right*—Reading type two-wire repeater installation.
*Left below*—Installation of 22-A-1 repeaters and associated signalling apparatus.
*Right below*—Close-up of composite ringer circuits.





of the various devices classified above is the "22-type" circuit. Here the significance of the "22" is "two element-two way", meaning that there are two distinct one-way amplifiers employed and that the repeater is arranged for use with the ordinary two-way telephone circuit.

Figure 247 shows such a circuit in simplified form with all the features outlined in the foregoing. Its operation is briefly as follows:

Let us assume that the subscriber at the west end of the connection is talking and that the greatly attenuated voice current from this station reaches the telephone repeater circuit at the bridge transformer associated with the west side of the repeater. It reaches the input transformer of the east amplifier through the connections at points 3T and 8T of the bridge transformer and the high frequency filter. In the vacuum tube circuit this energy is amplified many times and is impressed on winding 2-5 of the east bridge transformer, and from the theory of this transformer, which we have previously studied, half of this energy will be transmitted over the east line while the remaining half is lost in the balancing network. If this network balances the line exactly, no part of the energy will reach the input of the west amplifying circuit. This will prevent any part of the energy being amplified and fed back toward the west side of the circuit which might cause "singing" if there was a similar slight unbalance in the west bridge transformer, permitting the energy to circulate in the repeater circuit or permitting the amplifiers to operate like the generator described in Article 110. For a conversation in the opposite direction the conditions are reversed and the energy will be amplified in the west amplifier.

It will be noted that between points 3T and 8T of the bridge transformer and the primary side of the input transformer of each amplifier is a network of inductances and condensers which form the high frequency filter. This filter is designed to prevent the passage of frequencies which are very high and not essential for the successful transmission of the voice. The reason for eliminating these is that it is very difficult to design a balancing network that will exactly balance the ordinary telephone line at these frequencies and at the same time balance it for the essential voice current frequencies. The network, therefore, balances the line at the voice frequencies, and is not required to balance it at these higher frequencies when the filter is employed.

We shall not in this Course take up the miscellaneous apparatus and circuit features for adapting the repeater circuit to standard Central Office practices. In general these will involve many relays, jacks, keys and similar devices which are common in other circuits, and will readily be understood by studying the complete circuit of any particular repeater installation.

Another very common form of telephone repeater is the "44-type" used particularly on 4-wire cable circuits. The theory of its use may be understood by referring to Figure 248 which is a diagram of a 4-wire cable circuit. Here we have a "22-type" repeater circuit "stretched out" with the "double tracking" extending over the entire distance (or a considerable portion of it) instead of being localized in one office. The entire line is on a 4-wire basis instead of a 2-wire basis and the amplifiers are located at properly spaced intervals along the line. Each one of these amplifiers would naturally have no bridge transformer associated with it inasmuch as these need be located at the terminals only. In practice the circuits of the "44-type" repeater are not essentially different from the single amplifier in the "22-type" repeater circuit. They are usually designed, however, to give much higher gains and

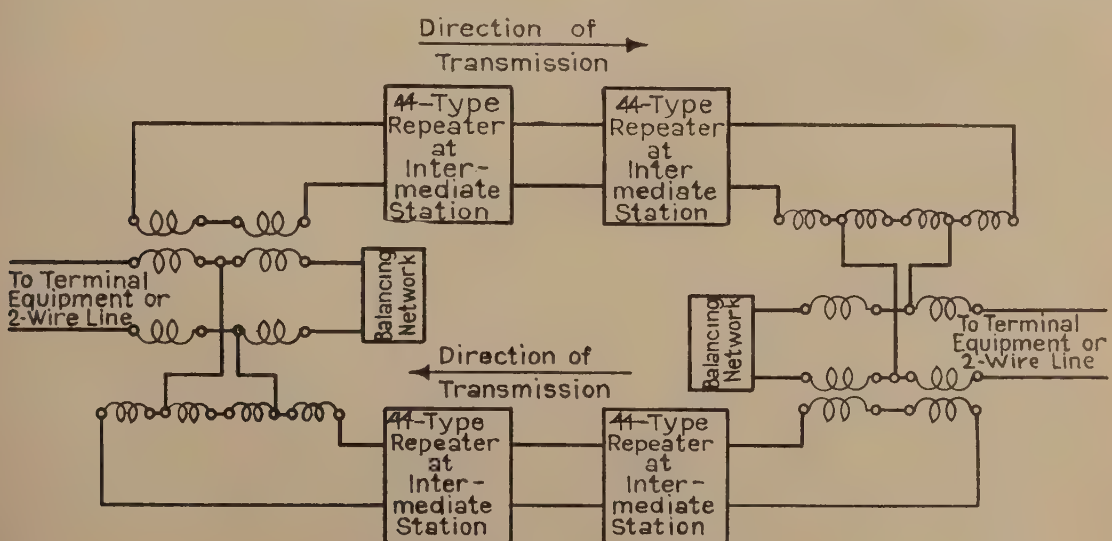



*Fig. 248—Layout of 4-Wire Circuit.*

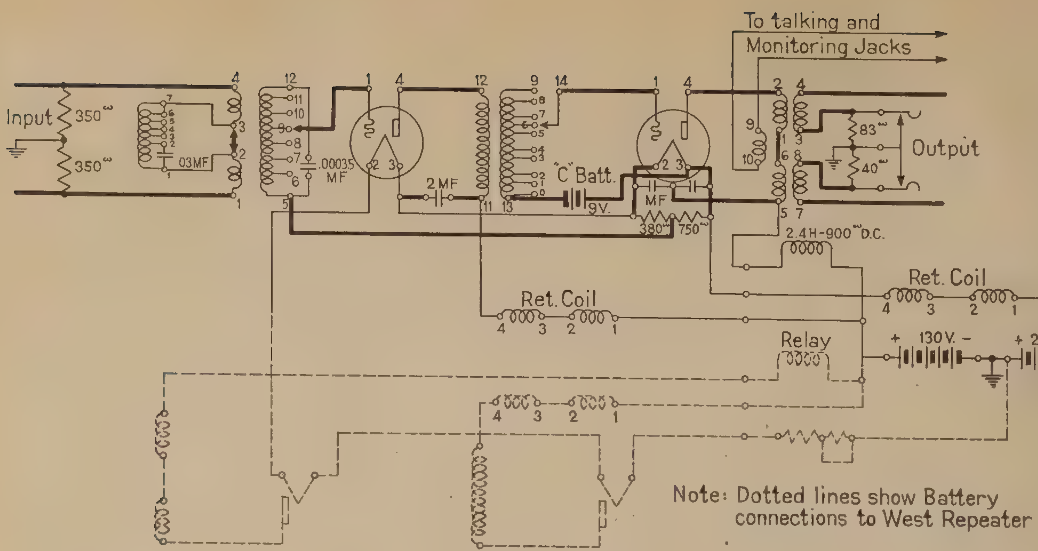



*Fig. 249—Simplified Circuit of 44-Type Telephone Repeater used on Long 4-Wire Cable Circuits.*

have two stages of amplification instead of a single stage of amplification. A simplified circuit for a typical two stage "44-type" repeater is shown in Figure 249.

A third form of telephone repeater less common than either the "22-type" or the "44-type" is called the "21-type". It is a "two way-one element" device and is connected at some intermediate point of the two-way circuit as shown in Figure 250. Here the line west, which must be identical in all respects to the line east, maintains the bridge transformer balance and prevents energy from the output of the single amplifier reaching its input. Of course the amplified energy in dividing at the mid point of the bridge transformer is fed both to the distant station and back to the speaking station. This is objectionable, and since the circuit has other limitations, at the present time it is not in very general use.

In telephone repeater operation it is well to remember that one-half of the energy is lost each time it passes through the bridge transformer circuit. In employing the TU as a unit for voice current attenuation this means that the actual gain of each amplifying element must be seven TU greater than the gain required for transmission from say, the line east to the line west. This is compensated for

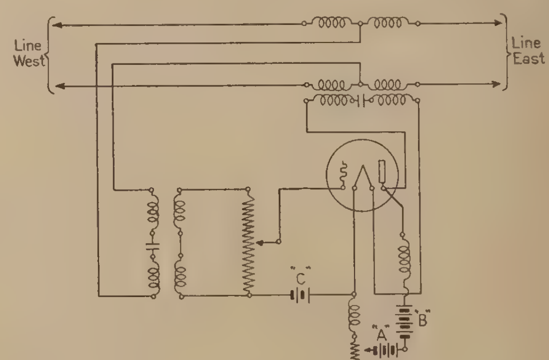



*Fig. 250—Simplified Circuit of 21-Type Telephone Repeater.*

in the calibration of the repeater's potentiometer, the various steps of which represent overall gain rather than single amplifying element gain.

# CHAPTER XIX

## TRANSMISSION THEORY OF LONG TELEPHONE LINES

### 112. Nature of Transmission Lines

Thus far we have analyzed the flow of alternating current in circuits having "lumped" constants, that is to say, whenever we have encountered one of the three properties, resistance, capacity or inductance we have considered it as something tangible and dissociated from other properties. The only capacity we have known has been that which might be effected by some device of definite size such as an actual condenser, and we have been able in every case to connect directly to the terminals of such a device. The same may be said of each resistance and inductance coil. Fortunately, this has simplified the makeup of the networks we have considered, but in taking up the long transmission line we shall find a different set of conditions. Though we shall not encounter any properties other than capacity, resistance and inductance, these will not be "lumped". They will be uniformly distributed along the entire length of the line, in fact they will be almost inseparably distributed. We can naturally expect, therefore, that circuits of this type will exhibit certain peculiarities which will make more difficult the analysis of the flow of current within them, which represents energy transmission.

The nature of a long transmission line to which is connected a source of alternating current energy, or we may say an alternating E.M.F., is fundamentally that of a medium for wave propagation. It is another manifestation of the various forms of energy we have about us in all nature such as sound, heat, and light, being transmitted through some medium, though in this case we are dealing with electrical waves rather than sound, heat or light waves. We speak of this form of transmission as "propagation". In all forms of "propagation" the energy is in the form of moving waves and encounters opposition at every point in the medium, which tends to dissipate or cause the energy to die out, and we speak of this as the "attenuation" of the energy. A typical illustration is the case of sound energy being transmitted through the atmosphere. The attenuation is lower to some extent if the sound energy is restricted to a column of the atmosphere such as the case where the voice is transmitted through a speaking tube. Voice current transmission over a long telephone line is simply a case of electrical wave propagation where the energy is restricted to a single channel.

In each of these phenomena for the propagation of the various forms of energy both the "degree of attenuation" and the "speed" at which the wave travels through the medium is going to depend upon the nature of the medium. Furthermore, there are going to be certain reactions that take place whenever the wave must pass from one medium to another. In the case of the speaking tube the distance over which we can talk and the velocity of the sound wave will depend to some extent on the density and humidity of the air within the tube, and if we could imagine a case where one end of the tube was filled with air of a different density and degree of moisture saturation from that at the other end, we might hear an echo at the speaking end due to a part of the energy being reflected back at the junction of the two transmitting mediums.

Perhaps a better illustration of the reflection phenomenon is the case of light which has a definite velocity through the atmosphere, but when it strikes a clear body of water such as a still lake will travel slower in the water than in the atmosphere. By our own observation, we know on the one hand that this light may continue through the water until it illuminates pebbles on the bottom of the lake, while on the other hand we find a mirrorlike reflection on the surface of the still water and know that some light is being reflected as it strikes the surface in the same way that light is reflected when it strikes the surface of a mirror. It is only reflected in part, however, as we have evidence that some of the light has penetrated the more difficult medium. In all forms of wave motion we may have this condition of reflection, and coming back to our transmission line for alternating current energy, we must deal with this as an effect distinct from the other two previously mentioned. All three effects will depend on the nature of the medium or media. Briefly, there are three general laws covering these phenomena:

a. The energy will be attenuated and the degree of its attenuation will depend on the combination of distributed capacity, distributed inductance, and distributed resistance (both in the series form as that of the conductors and in the shunt form as that of leakage).

b. There will be a definite speed at which the wave travels, which will depend upon the electrical characteristics of the transmission line as established by the properties mentioned in "a" above.

c. There will be a reflection of energy whenever the wave must pass the junction of one transmission line with another, where the two lines have different electrical characteristics.

To analyze alternating current flow to the most accurate degree under such conditions, where we have wave propagation rather than simple flow through a localized circuit with "lumped" properties and must take into consideration the circuit properties as they exist and the conditions brought about by the uniform distribution of these properties over great lengths, would naturally involve the

higher branches of mathematics. For most practical purposes, however, and for the applications that we meet in every day telephone work we may closely simulate or approximate the electrical make-up of any transmission line by some form of circuit having "lumped" properties. In order that we may obtain a clear idea of the processes involved in as simple a manner as possible, however, we may profitably first consider this general problem on a direct current basis. In doing this, we will need to remember that such a treatment is largely hypothetical as both telephone and telegraph transmission are essentially alternating current phenomena; but we will, nevertheless, be able to establish certain general principles more easily than by handling the problem as an alternating current one from the beginning. Then having established these principles, we may revert to our alternating current transmission problem and make such modifications as are necessary in order that they may apply equally well to the alternating current case.

### 113. The Transmission System

**Any transmission system consists of three essential parts; a source of energy, a medium over which it is desired to transmit energy to a receiving device, and the receiving device itself, which usually converts the electrical energy into some form more useful.** In a power transmission line an electrical generator may be the source of energy; high voltage lines with transformers at either end may be the transmitting medium; a motor, lamp or heater may be the receiving device for converting electrical energy into some other useful form. In a long distance telephone connection a transmitter may be considered as a source of energy; the line from the speaking party to the listening party with all of its associated conductors, coils, and connections may be considered as a transmission medium; and the telephone receiver at the distant end may be considered as the third part of such a transmission system or the device which converts tiny electrical currents into audible vibrations of air called **sound waves.** Regardless of the kind of system we must have these factors.

### 114. Transfer of Power

If a system is to accomplish its purpose it must be so designed that the energy transmitted from the source to the receiving device is sufficient to successfully operate the receiving device. As a secondary consideration it may be designed for power efficiency; that is, regardless of the magnitude of the power delivered to the receiving device, the power lost in transmitting energy from the source must be kept a minimum. Although this is important in any transmission system, its special importance is in power transmission. In telephone work we probably think more of the primary purpose, that is, the **system's effectiveness in transfering the maximum quantities of power to the device** regardless of what percentage may be lost.

To illustrate the principles of power transfer and power efficiency, let us consider a direct current power distribution system in a small town. Such a system is usually a complicated network, consisting of a combination of many series and parallel resistances. When connecting a lamp to the lighting mains, we are concerned primarily in the transfer of power to the lamp. The lamp then, is the receiving device; the wiring from the lamp to the mains is the transmitting medium and the mains the source of energy. Looked at in this manner, the source of energy is no longer a simple device, such as a battery but is itself an energized network of very complex make-up. Moreover, the current and voltage distribution in this energized network will be influenced by the presence or absence of the lamp; current and voltage values elsewhere in the system will change as the lamp is connected to or disconnected from the mains. We know that our receiving device has a constant resistance and for a constant voltage will take a definite electrical current. We further know that the power that is going to be expended in the device is equal to its resistance multiplied by its current squared. This we may call the **useful expended power.** But if the current going from the source of electromotive force must traverse other resistances or other parts of the complicated network, as is the usual case, part of the power which is actually delivered by the source of electromotive force, on account of the connection of the particular device, will be lost in the network or distribution system. The power received by the device divided by the power expended by the source on account of its connection is called **power efficiency.** This will be increased with increase in resistance of the device. We, therefore, have the most efficient operation when the receiving circuit is one of very high resistance.

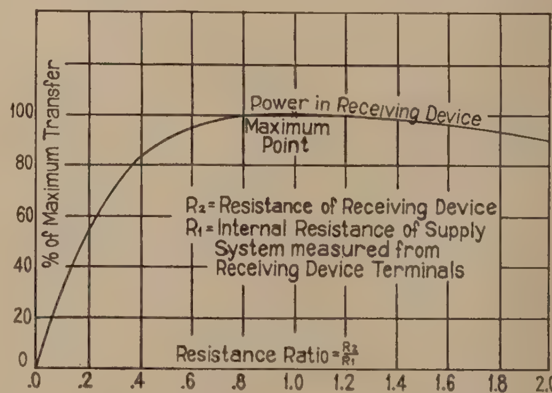


*Fig. 251—Ratio Curve for Power Transfer.*

On the other hand, we may be interested in receiving all of the power possible regardless of whether the operation under such circumstances is efficient or not. In the case of a telephone receiver at the end of a long transmission line, we are primarily interested in the receiver taking from the electrical system the maximum amount of energy

(in a given time). **The condition for maximum transfer of power is obtained when the resistance of the receiving circuit is equal to the resistance of the network to which it is connected, measured across the receiving terminals.** The simplest application of this is secured by connecting to a battery a resistance equal in magnitude to the internal resistance of the battery. In this case the battery will transfer to the external circuit the maximum amount of power, but in doing so will operate at an efficiency of only 50%.

Figure 251 shows a curve which represents the power of the external circuit for various ratios of the resistance of the external circuit to that of the internal circuit. Figure 252 shows the efficiency for the same conditions. Table XIII gives the values from which these curves were plotted.

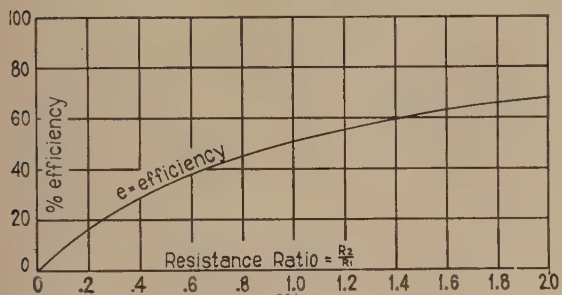



*Fig. 252—Efficiency Curve for Power Transfer.*

### 115. Pollard's Theorem

For the purpose of simplifying electrical calculations we can consider any electrical system as one network supplying energy to another, or we can consider a simpler case of one network supplying energy to a simple series circuit. **For every energized network there is an equivalent simple electrical circuit which consists of an E.M.F. and a resistance in series.**

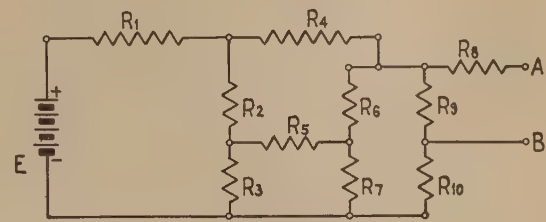



*Figure 253*

This means that regardless of how complicated an electrical circuit may be its effect in supplying current to any other circuit connected to it at two designated terminals is equivalent to some source of electromotive force in series with a resistance, or we may say is equivalent to a source of electromotive force such as a battery having an internal resistance of a definite value. This principle is called **"Pollard's Theorem"** and Figure 253 illustrates its use. E is a source of electromotive force connected to a complicated network; A and B are terminals to a particular branch of the complicated network. If it is desired to connect some receiving device to these terminals the effect of this electrical system on the receiving device will be the same as that of the electrical system shown by Figure 254 where E′ is the electromotive force measured across

TABLE XIII

**The Comparative Percentages of Power Delivered to a Receiving Device for Various Ratios of its Resistance to the Internal Resistance of the Supply System, and the Efficiency at which Power is Supplied to the Receiving Device for the Same Ratios.**

| Value of $R_2$ | % of Maximum $P_2$ $= 100 \times \frac{4 R_2 R_1}{(R_1 + R_2)^2}$ | % Efficiency $= \frac{100}{\frac{R_1}{R_2} + 1}$ |
|---|---|---|
| 2.0 $R_1$ | 88.9 | 66.7 |
| 1.1 $R_1$ | 99.8 | 52.4 |
| 1.0 $R_1$ | 100. | 50. |
| .9 $R_1$ | 99.7 | 47.4 |
| .5 $R_1$ | 88.9 | 33.3 |
| .2 $R_1$ | 55.6 | 16.7 |

the terminals A and B of Figure 253 and R′ is the resistance measured or calculated from the same terminals with the electromotive force E short-circuited. Pollard's Theorem may be briefly stated as follows:

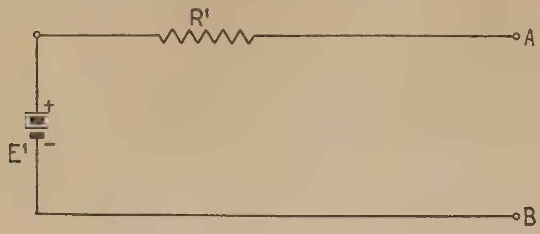



*Figure 254*

**The current supplied to an electrical device connected to two terminals of any electrical system is equal to the potential measured across these terminals before the device is connected, divided by the resistance measured or calculated across these terminals with the source of E.M.F. short-circuited, plus the resistance of the receiving device.**

## 116. Equivalent Networks

Pollard's Theorem gives us a method of substituting an equivalent circuit for any complicated electrical system, but in so doing we are required to replace the source of electromotive force with one having another value. It is often desired to determine **the simplest equivalent network for a complicated electrical system which will supply to some receiving device the same current as the electrical system and will take from the same source of electromotive force the same current as the electrical system.** A network consisting of three resistances of proper value arranged in the form of a T as shown by Figure 255 can always be substituted for any network, regardless of how complicated, and fulfill these conditions. For example, the circuit in Figure 255 may be substituted for that

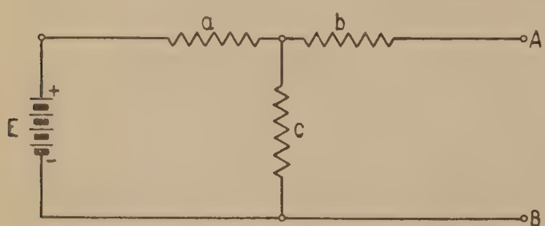



*Figure 255*

shown by Figure 253, and the current supplied to this system by the electromotive force E will remain unchanged, and the current received by a device connected to the terminals A and B will be the same. In determining values for the three resistances in an equivalent T network such as is shown by Figure 255, the following equations may be used.

$$\text{Resistance of a} = R_1 - c \quad \ldots \quad (72)$$

$$b = R_3 - c \quad \ldots\ldots \quad (73)$$

$$c = \sqrt{(R_1 - R_2)\,R_3} \quad (74)$$

where $R_1$ is the calculated (or measured) resistance of the complicated network at the terminals connected to the source of E.M.F. with the receiving device terminals open, $R_2$ is the same with the receiving device terminals short-circuited and $R_3$ is the resistance of the complicated network calculated (or measured) from the receiving device terminals with the source terminals open.

## 117. Multisection Uniform Networks

A long transmission line can be exactly represented electrically by a simple three-element equivalent network such as was discussed in the preceding Article, but the determination of the values of the three arms of the network involves in this case the use of certain higher branches of mathematics.

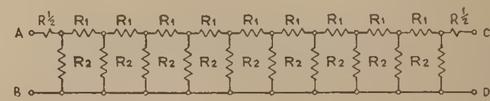



*Fig. 256—Multi-Section Uniform Network.*

For most practical purposes, however, we may deal with the transmission line by considering it as consisting of a number of separate sections. Treating at this time the direct current case, we shall here assume an approximately equivalent network for a transmission system such as a grounded telegraph wire 50 miles in length and having a uniform leakage to ground throughout. We can imagine such

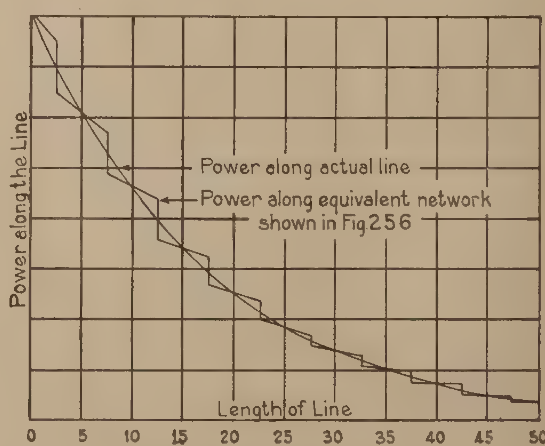



*Fig. 257—Comparison of Multi-Section Network with actual line.*

a circuit as 10 uniform sections, and for our purpose may consider the leak to ground in each 5-mile section as concentrated at the middle point. With

these assumptions our circuit may be represented by the network shown in Figure 256. Such a network is called a **multisection uniform network** because it consists of a number of identical units joined together. While a network thus constructed is not identical to the actual telegraph wire, we can construct one as nearly identical as we may desire by making our sections shorter in length. In this particular case a 10-section uniform network would give a very small error in calculations, for a receiving instrument connected across terminals C and D. If the smooth curve of Figure 257 represented energy values for various points along the actual telegraph wire, the broken line would approximately represent energy values in each section of the network.

Knowing the value of each unit in the network shown in Figure 256, we may calculate the current that would be received by a resistance connected across C and D with a definite electromotive force applied to A and B by using Ohm's law and Kirchoff's laws in the same manner that we have applied them to other networks. This procedure, however, for very long transmission lines, is very laborious and may be simplified by use of an **attenuation** formula, which will be discussed after defining just what is meant by characteristic resistance.

## 118. Characteristic Resistance

If we assume a telegraph instrument connected to terminals C and D of Figure 256, it would receive the maximum amount of power from the uniform network if its resistance were equal to the resistance of the network as measured across these terminals. Likewise the network would receive the maximum amount of power from any energized circuit to which it might be connected at the points A and B if its resistance measured across A and B were equal to the resistance of the energized circuit. This we learned from the principle of maximum power transfer. But before connecting an energized circuit for sending to A and B or a circuit for receiving to C and D, let us measure the resistance of the network at A and B and then construct a simple resistance $R_o$ of this measured value and connect it to C and D.

If we then take a new measurement across A and B, we shall have a value different from that of the first measurement. The value we would obtain for this second condition, however, would be equal to that of a multisection uniform network having exactly twice the number of sections of that shown by Figure 256. This is evident when we consider that in connecting the resistance $R_o$ to the network of Figure 256, as shown by Figure 258, we in effect doubled the length of the multisection network because the resistance $R_o$, connected to the terminals C and D, is equal to the resistance of the network measured from A and B when the terminals C and D are open. Therefore, Figure 258 is equivalent in all respects to a 20-section network open at the distant end instead of a 10-section network as shown by Figure 256. If the new measured resistance value is substituted for the resistance $R_o$ in Figure 258, we shall then have a network equivalent to a 30-section uniform network. If we again take measurements and replace $R_o$ with the still newer value and continue this practice indefinitely, each time in effect increasing the length of the network by ten sections, we will eventually have the equivalent of a line so long that anything connected to its distant end will have no effect upon the current which the sending element delivers to the line at the terminals A and B. Thus, either short-circuiting or opening the distant end would not affect the equivalent resistance of the line.

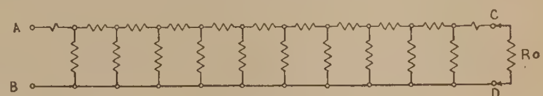



*Figure 258*

This equivalent resistance or the resistance of a network having an infinite number of sections is called the **characteristic resistance** and its value can be calculated from the relationship

$$R_o = \sqrt{\tfrac{1}{4} R_1^2 + R_1 R_2} \quad \ldots\ldots\ldots \quad (75)$$

where $R_1$ and $R_2$ are the elements of a network as shown in Figure 256 and $R_o$ is its characteristic resistance. If this characteristic resistance is substituted for $R_o$ and if the sending circuit supplying energy to the line is so designed as to have the same resistance as $R_o$ we shall then have the conditions of maximum energy transferred both from the sending circuit into the line at A and B, and from the line into the receiving telegraph instrument at C and D. While in practice this condition may not be generally applied to telegraph operation it does apply to long distance telephone circuit operation. Characteristic resistance treated here bears the same relation to a direct current transmission line as characteristic impedance bears to an alternating current transmission line. In both cases the principle is the same. It is paramount in the operation of long distance telephone circuits from two viewpoints—first, an efficiently designed system for simple voice current transmission and second, successful telephone repeater operation which requires balancing networks.

If in every case it were possible to connect receiving devices to sources of energy without intermediate lines the receiving device could be designed with respect to the source of energy or vice versa and maximum power transfer secured by comparatively simple methods. But, as we have seen, the intermediate transmission line complicates the problem; especially when at best a considerable portion of the energy must be lost in the line. Ordinarily the physical nature of the transmission medium is more or less fixed. It is, therefore, necessary to design the apparatus connected to it with respect to its characteristic resistance (or impedance) rather than to design one unit with respect to the other.

### 119. Attenuation

This subject, too, has little importance when applied to direct current circuits such as the telegraph circuit previously discussed, but it likewise may be treated more clearly from the direct current aspect. We shall define, therefore, at this time what is meant by attenuation and the use of attenuation formulas in calculating current values at points along, or at the distant end, of a transmission line. If in Figure 258 **the multisection uniform network has an infinite number of sections or is terminated in its characteristic resistance $R_o$, the ratio of the current leaving any one section to that entering the section will be the same regardless of what section is considered.** That is,

$$\frac{I_2}{I_1} = \frac{I_3}{I_2} = \frac{I_4}{I_3} = \text{a constant} \ldots\ldots\ (76)$$

To illustrate this, let us assume that the current entering the network at A and B is decreased at the end of the first section to a given fractional value, for example ½; then the remaining current, which is ½ of the original, at the end of the second section will be likewise decreased ½ or will leave a remaining current of ¼ of the original, which at the end of the next section will be ⅛ of the original, and at the end of the next section will be $^1/_{16}$ of the original, and thus continue indefinitely. This "dying out" or attenuation of the current is due to a part of the current in each section returning through the shunting resistance instead of flowing toward the receiving end, and thereby becoming lost in so far as the actual transmission from one end of the network to the other is concerned. If, for example, we desire to calculate the current value at the distant end of a 10-section uniform network we must, therefore, multiply the ratio of the current entering each section to that leaving each section by itself 10 times, or take the 10th power of the fraction $I_2/I_1$.

Such calculations are usually made by the use of logarithms. This permits an equation to be written giving the ratio of the current at the receiving end, $I_n$, to the current at the sending end, $I_1$ as follows:

$$I_n/I_1 = 1/e^{n\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ (77)$$

where n is the number of sections, e is the base of the Naperian logarithm system, and $\alpha$ is the **attenuation constant.** The value of $\alpha$ can be calculated from the following equation:

$$\alpha = \log_e \frac{R_1/2 + R_2 + R_o}{R_2} \ldots\ldots\ (78)$$

in which $R_1$ is the series resistance per section, $R_2$ is the bridged resistance per section and $R_o$ is the characteristic resistance. The same equation may be expressed using common logarithms as follows:

$$\alpha = 2.303 \log \frac{R_1/2 + R_2 + R_o}{R_2} \ldots\ (79)$$

# CHAPTER XX

## TRANSMISSION THEORY OF LONG TELEPHONE LINES

(Continued)

### 120. The Transmission Line as a Multisection Network

Now having made use of a direct current analysis of the general problem of transmission over long distances to establish certain definitions and methods of attack, we may turn our attention to the less artificial but somewhat more complex problem of alternating current transmission. Let us assume that Figure 259 represents a very long telephone line with alternating current energy (such as that coming from a telephone transmitter) applied at one end, and some receiving device of an impedance $Z_r$ connected at the distant end. We know


*Fig. 259—Telephone Line with Uniformly Distributed Constants.*

that such a line has series resistance. By short-circuiting the receiving device at the distant end we could determine with a Wheatstone bridge the actual value of the series resistance from one end to the other. We further know that it has series inductance, because there must be the equivalent of interlinkages of the magnetic lines of force from one coil turn to another since in this case the lines of force set up by the current flowing in one wire will cut the other wire as they contract and expand and will create an induced E.M.F. in the same way as adjacent loops of a coil, though perhaps to a much less degree for the same length of conductor. Yet, since the line is very long, the overall series inductance will be appreciable.

We further know that the line has some leakage which in any practical case will depend upon atmospheric conditions, but the insulation will never be so perfect that some leakage cannot be detected with a sufficiently sensitive instrument. There is yet one other property of the line. If it is open at the distant end it will be found to act very much like a condenser. When a battery in series with a sensitive meter is connected to it there will be a throw of the needle showing that the line temporarily is taking current to charge the two wires as though they were plates of a condenser.

Now let us assume that we know the resistance, inductance, leakage, and capacity of each mile of the circuit, and also its total length. If we evaluate the constants of the circuit in its entirety and attempt to use these values directly to build a simple network that will simulate the line, we will find the task impossible. Even a T-network made up of these "nominal" values will fail to simulate the line if the latter be of any great length, and the greater the length the greater will be the electrical dissimilarity between line and network. We could, of course, construct an equivalent T-network, using constants determined by measurements as explained in the preceding Chapter, which would exactly simulate the line, but we should find this T quite unlike the "nominal" T. * However, by taking shorter sections of line to simulate, we find a closer agreement between the line and the "nominal" T, so that by considering the line as made up of a large number of extremely short sections, and constructing a multisection uniform network as illustrated in Figure 260, we can approximately simulate the line.

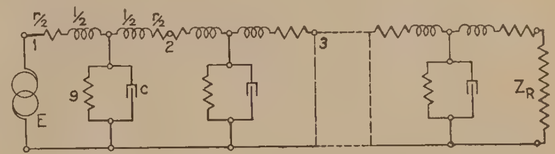



*Fig. 260—A Uniform Multisection Network.*

The degree of accuracy to which we approximate the line is going to depend on how far we go in breaking up the quantities into smaller parts for making a greater number of tiny sections for the uniform multisection network. To begin with, we shall take an extreme case. Let us assume, for instance, that we have a circuit 1,000 miles long and are going to construct a network section for each foot, giving more than 5,000,000 sections for the network. Certainly we could not question the accuracy with which such a multisection uniform network would approximate the actual line. Assuming, therefore, that we have succeeded in so breaking up our distributed properties into tiny "lumped" properties which can be connected into a form of network, let us now accept this network as illustrated by Figure 260 as equivalent for all practical purposes to the actual transmission line illustrated by Figure 259.

Now our interest in this network lies in—

a. The current that will leave the generator at the sending end and flow into the network. This will be determined solely by the impedance the network presents at the "voltaged"

*The relationship between these two networks is not a simple one and necessitates the use of hyperbolic trigonometry for its determination.

end when connected to the generator. If $V_o$ is the terminal voltage of the sending device, and $I_o$ the entering current, then $I_o = V_o/Z_o$ where $Z_o$ is called the "sending end impedance" of the line (and when the line is infinitely long it is called the "characteristic impedance" of the line). Since our line is 1,000 miles long and will for all practical purposes draw the same sending current from the generator as an infinite line, we can consider $Z_o$ in this case as the "characteristic impedance".

b. We are next interested in what part of the energy leaving the generator will eventually reach the receiving device at the distant end, or since energy depends on both voltage and current we are interested in what part of the generator's voltage will be impressed across the terminals of $Z_r$ or what part of the generator's current will flow through $Z_r$.

c. For many transmission considerations we are also interested in the time required for the energy leaving the generator to reach the receiving device, or in other words we are interested in the speed of wave propagation from one end of the line to the other.

Theoretically, it **is not altogether impossible** to treat Figure 260 as any complicated network and, step by step, to calculate the impedance $Z_o$ as long as the number of sections is finite. In this case we are dealing with 5,000,000 sections, and it would **be possible** to calculate the current flowing in each branch of the network or even through the distant receiving device but certainly such extended computations would be impracticable and almost endless, and the calculations for uniform multisection networks are never made in this laborious manner. By a certain mathematical analysis we derive short cuts, based upon the following:

Knowing the makeup of the network sections, we might describe each as a series impedance z due to the series resistance and inductance of one foot of line, and a bridged impedance $z_s$, due to the bridged leakage and capacity of one foot, or instead of using $z_s$, we may for convenience use its reciprocal which is called the "admittance" and designated by the symbol y. From previous Chapters, we express z and y in terms of the resistance, inductance, conductance (or leakage) and capacity for one foot of line. Let us represent these four quantities by r, l, g, and c * respectively. Now, the series impedance contains only r and l and is given by the equation—

$$Z = \sqrt{r^2 + (6.28\,fl)^2},\ \Theta_1 = \tan^{-1}\frac{6.28\ fl}{r} \quad \ldots\ (80)$$

In the same manner, since g and c are bridged properties, we may write—

$$y = \sqrt{g^2 + (6.28\,fc)^2},\ \Theta_2 = \tan^{-1}\frac{6.28\ fc}{g} \quad \ldots\ (81)$$

*Here it must be remembered that c is in farads and not microfarads.

An inspection of the makeup of each section would lead us to expect the characteristic impedance, $Z_o$, to become greater as z becomes greater, for the series impedance, z, is tending to decrease the current which the generator attempts to make flow. Then again, we should expect an increase in the impedance of the shunt across each tiny section, the admittance of which we have designated as y, to permit less current to be shunted at each section and returned to the generator, thereby in its overall effect decreasing the amount of current that the generator would feed into the network, or in other words we should expect the quantity $Z_o$ to become greater as $z_s$ becomes greater or as y, which is the reciprocal of $z_s$, becomes smaller.

The value of $Z_o$ will tell us something of the nature of our transmitting medium, and since it is called characteristic impedance it corresponds to the term "characteristic resistance" of the D.C. line, as discussed in Article 118. It can actually be proven that the value of $Z_o$ for an infinite line may be determined from a simple equation expressed in the terms z and y, as follows:

$$Z_o = \sqrt{\frac{z}{y}} = \sqrt[4]{\frac{r^2 + (6.28\,fl)^2}{g^2 + (6.28\,fc)^2}} \quad \ldots\ldots\ (82)$$

Having determined the characteristic impedance of the line and knowing the terminal voltage of the generator we can easily determine the current supplied to the line, or the energy supplied to the line.

Our next interest, as stated by "b" in the foregoing, is the part of this current or energy which will eventually reach the receiving device. Clearly it would be endless to proceed with ordinary network calculations but again the calculations are simplified if we know **the degree to which each section of the network causes the current wave propagated along the line to "die out".** Knowing this, we may say that the same "attenuation" when the line is treated as infinite applies to the voltage, because **the impedance for an infinite line is always the same when looking away from the sending end regardless of what junction of sections may be considered.** To illustrate, if we should open the multisection network of Figure 260 and measure the impedance looking away from the generator at point "3", we would have the same result as if we measured the impedance connected to the generator. We would get the value $Z_o$ which is the characteristic impedance of the line, and since $Z_o$ always remains the same and must always be equal to V/I at any point along the network, V and I must be attenuated in the same ratio. If I becomes ½ of its value at some point along the line, then V must become ½ of its value, etc.

Now as we noted in Article 119, inasmuch as all sections are identical in their makeup it can be seen that the loss or attenuation in each section will be the same, so that if the ratio of entering current to leaving current for the first section is nine-tenths, the ratio of currents for the second section and any succeeding section will be nine-tenths. Thus if we

know the ratio of the current at point "2" to the current supplied the section by the generator, which we may represent by $I_1/I_o$, and wish to find the current at some point along the line, we could multiply this ratio by the succeeding ratios for each section as follows:

$$\frac{I_n}{I_o} = \frac{I_1}{I_o} \times \frac{I_2}{I_1} \times \frac{I_3}{I_2} \times --- \frac{I_n}{I_{n-1}}$$

or since

$$\frac{I_1}{I_o} = \frac{I_2}{I_1} = \frac{I_3}{I_2} \text{ etc.}$$

$$\frac{I_n}{I_o} = \left(\frac{I_n}{I_{n-1}}\right)^n \dots\dots\dots\dots\dots\dots (83)$$

This is sometimes written $k^n$ where k is the value of any one of these ratios, but for convenience in computation this ratio is usually expressed by logarithms—

$$\log_e \frac{I_n}{I_o} = -n\gamma \text{ or } 2.303 \log \frac{I_n}{I_o} = -n\gamma \dots\dots\dots (84)$$

where

$$\gamma = \sqrt{zy} = \sqrt[4]{[r^2 + (6.28fl)^2]\,[g^2 + (6.28fc)^2]} \quad (85)$$

and n denotes the number of sections traversed by $I_n$. Here we have a mathematical short cut for our network calculations, which expressed in words is as follows: **If we wish to know the relation between the current at any point along a transmission line and that delivered by the generator at the sending end, we can multiply the propagation constant of one section, $\gamma$, by the number of sections traversed, and the product taken negatively is 2.303 times the logarithm of the current ratio.**

But the quantity $\gamma$ is more than some constant that gives the mere dying out effect of the current. The ratio of current $I_n$ to $I_o$ is a relation of both effective values and phase difference as both $I_n$ and $I_o$ are vectors and are not necessarily in phase. This must be taken care of by treating $\gamma$ as we treat all vectors (and $\gamma$ is a vector quantity because being equal to $\sqrt{zy}$ where both z and y are vectors it too must be a vector). We must separate, therefore, the constant $\gamma$ into two components, one of which applies to "attenuation" alone and the other of which has to do with speed of propagation. We may write then, that

$$\gamma = \sqrt{\alpha^2 + \beta^2}, \qquad \phi = \tan^{-1}\frac{\beta}{\alpha} \dots\dots\dots (86)$$

where $\alpha$ is the symbol for the **attenuation constant** and $\beta$ is the symbol for the **wave length constant.** By combining equations (85), and (86) the value of both $\alpha$ and $\beta$ can be expressed by equations employing the terms r, l, g, and c, or the unit constants of the line, thus—

$$\alpha = \sqrt{\tfrac{1}{2}\sqrt{[r^2 + (6.28fl)^2]\,[g^2 + (6.28fc)^2]} + \tfrac{1}{2}\,[gr - (6.28f)^2lc]} \dots\dots\dots\dots\dots\dots (87)$$

$$\beta = \sqrt{\tfrac{1}{2}\sqrt{[r^2 + (6.28fl)^2]\,[g^2 + (6.28fc)^2]} - \tfrac{1}{2}\,[gr - (6.28f)^2lc]} \dots\dots\dots\dots\dots\dots (88)$$

where f denotes frequency in cycles per second.

In the foregoing discussions of Figure 260 we have in each case designated some point along the line such as point "n" at which we wish to determine the current flow. This applies to an infinite line. If, however, $Z_r$ is equal to $Z_o$, or in other words if the line at the distant end is terminated in a receiving device having an impedance equal to the characteristic impedance of the line, or if an inequality ratio repeating coil is inserted between the receiving device and the line so as to properly match these impedances, we could take the point "n" as the distant terminal and apply equation (84) for calculating the current at the distant end. Of course, where we are dealing with attenuation alone we may express (84) as follows:

$$-n\alpha = 2.303 \log \frac{I_n}{I_o} \dots\dots\dots\dots\dots\dots (89)$$

where $I_n/I_o$ is the ratio of effective current values only, which are not vectors. In other words the ratio now becomes an actual comparison between current delivered to current sent, ignoring, of course, that there may be some phase difference between the two currents. To convert this to energy, we can use the expression—

$$P_o = E_oI_o \cos\Theta$$

and

$$P_n = E_nI_n \cos\Theta$$

Now

$$\frac{E_o}{I_o} = Z_o \quad \text{and} \quad \frac{E_n}{I_n} = Z_o$$

whence

$$\frac{E_o}{I_o} = \frac{E_n}{I_n} \quad \text{or} \quad \frac{E_n}{E_o} = \frac{I_n}{I_o}$$

so that

$$\frac{P_n}{P_o} = \frac{E_nI_n\cos\Theta}{E_oI_o\cos\Theta} = \frac{E_nI_n}{E_oI_o} = \left(\frac{I_n}{I_o}\right)^2 \dots (90)$$

But equation (89) can be written—

$$2.303 \log\left(\frac{I_n}{I_o}\right)^2 = -2n\alpha \dots\dots\dots (91)$$

Combining this with (90) we have—

$$2.303 \log \frac{P_n}{P_o} = -2n\alpha \dots\dots\dots\dots\dots (92)$$

The energy, therefore, may be said to die out or attenuate in a ratio which is the square of the current ratio.

In the foregoing we find for the most part a mathematical significance of $\alpha$ and $\beta$. Let us now

analyze the physical circuit to determine what actually happens as the current is sent from point to point. In order to simplify the analysis we shall start with an actual cycle of E.M.F. impressed on the sending end of a multisection network and consider separately the effects of inductance and capacity on the propagation of this wave.

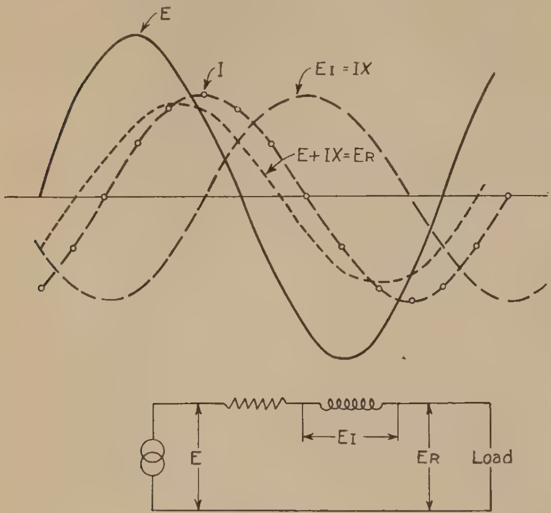


*Figure 261*

From our previous study we know that inductance acts to cause the current to lag behind the impressed voltage, so that in a circuit made up of resistance and inductance we would expect a lagging current. Figure 261 shows the time relationship between voltage and current in such a circuit, where E is the voltage curve, and I the current curve. This current flowing through the inductance sets up an induced E.M.F. or IX drop as shown by $E_1$ which combines with the original voltage E to give the "resultant voltage" $E_R$ on the load side of the inductance. The curve $E_R$ is obtained by adding E and $E_I$ and it will be observed that the resulting curve lags E, the original voltage. A circuit containing resistance and capacity, on the other hand, produces a leading current as shown by Figure 262, and this current will produce an IR drop which will be opposite in phase with the current. Now if we combine the IR drop and the voltage, we obtain the resultant voltage $E_R$ which exists across the condenser and this voltage likewise lags E, the original voltage.

In both cases we have obtained a resultant voltage which lags behind, and is smaller than the impressed voltage. In other words **bridged** capacity assists **series** inductance in the phase retarding effect. Due to the presence of reactance, therefore, the voltage has been "held back", so that the maximum voltages act later than they would if the reactance were removed. In other words, **the voltage wave has been slowed down.** Here, then, we have an explanation of the **significance** of the wavelength constant; it is merely an index figure to show how much the wave is retarded. Let us now apply our knowledge to the further study of the transmission line which we have represented by a series of T-sections. Each section, due to resistance and leakage absorbs energy and therefore reduces the voltage which can act on the next section. Further, the voltage available at the next section lags behind the voltage impressed on the section, so that as we move away from the generator the acting voltages are lagging farther and farther behind the generator voltage. Here we have a connecting link between geographical **distance** travelled along the line and **time.**

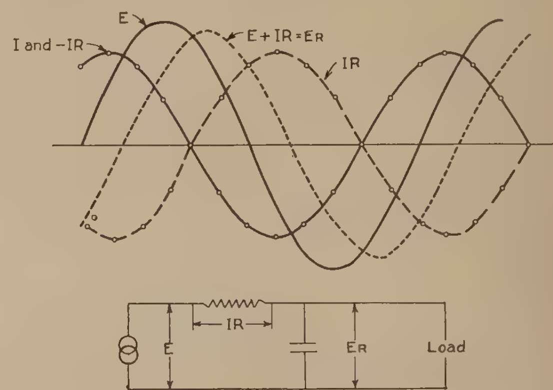


*Figure 262*

To bring this out clearly, let us assume that we take our sections of such a length that for a frequency of 796 cycles the time lag between voltages can be represented by 30 degrees per section on the **time-voltage** diagram; if we simulate by each section eighteen and three-quarters miles of non-loaded 104 open wire circuit, we will obtain such a relationship. In order to make the story complete, we will also consider the reduction in voltage magnitude due to resistance and leakage loss; the voltage ratio will be 0.934 per section. If we assume the original voltage $E_o$ to be 10 volts, the voltage at the end of the first section, $E_1$, will be 9.34 volts, lagging 30° behind $E_o$. $E_2$, at the end of the second section will be 0.934 x 9.34 or 8.72 volts, lagging 30° behind $E_1$ or 60° behind $E_o$. If we represent the voltages at various points by vectors we will obtain a system of vectors as shown in Figure 263-B where the multisection network is shown as Figure 263-A and the voltage acting at each junction is directly below.

Since the ratio of current to voltage is constant it follows that the chart representing currents will have the same form with each vector proportional and removed by an angle $\Theta$ from the corresponding voltage vector, where $\Theta$ is the angle of the "characteristic impedance" $Z_o$. Thus we may treat a similar figure such as 263-C as a "distance-current diagram" where the vectors $I_o$, $I_1$, $I_2$, etc., show the magnitude and relative phase of the currents at the network junctions. If now we refer all the current vectors to a common reference point we will obtain a broken curve such as that of Figure 264-A which

shows graphically how the currents at various points are related. In this figure the vector $I_o$ = G-0 is the current entering the first section and $I_1$ = G-1, the current leaving that section. Then the vector 1-O must be the current that passes through the shunt in the first section, because the sum of the current through the shunt and the current going ahead gives 1-0 as the resultant of the vector diagram. This is perhaps more clearly illustrated by Figure 264-B. For the same reason 2-1 will be the current passing through the second shunt, etc.

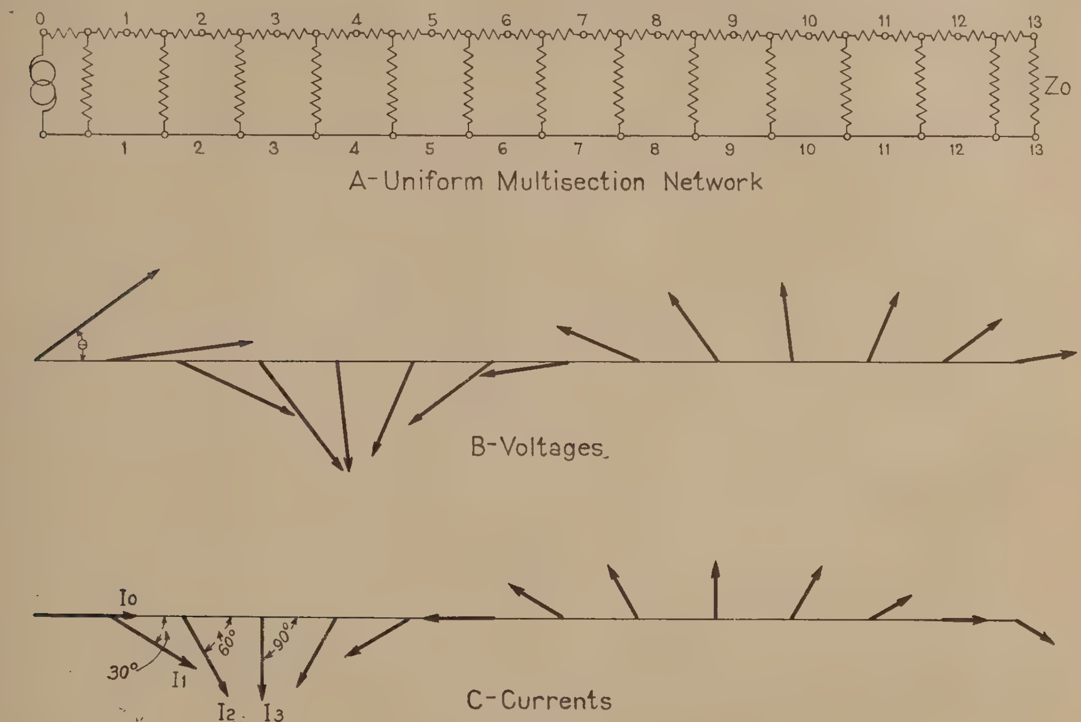


*Figure 263*

We may, therefore, conceive of the total entering current as the resultant of a number of component currents which flow from the generator through the various shunt paths and back to the generator, each component of a different magnitude and phase. The effect of these components can be observed since at certain junctions, the line current is flowing in the opposite direction to that taken by the entering current; at other points there is a 90° phase difference between the two; and at still other points there is no phase difference. In other words, the current vector may be considered as rotating about G, rotating through 30° for every section traversed and diminishing in value 6.6% in each section.

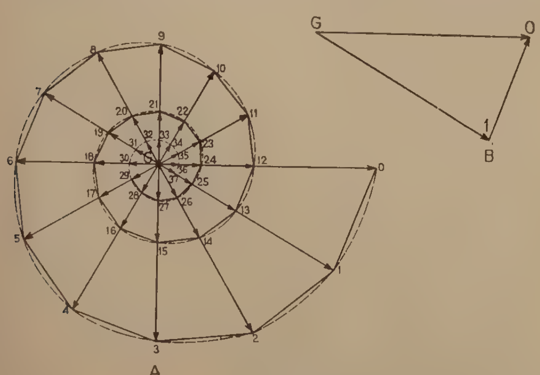


*Figure 264*

Figures 263 and 264 show the effective values of the current at certain points along the line and their relative phase positions. These diagrams are independent of time, i.e. they are applicable at any and all times. If on the other hand, we select a given instant of time and plot the instantaneous values of the current at the same points along the line, we obtain the curve shown in Figure 265 which shows clearly how the current reverses in direction as it passes through the various sections. A little study of this curve suggests that it is related to the sine curve, and such is actually the case. Due to the decay of current from section to section the sine wave is somewhat distorted, but if the decay were eliminated, the curve would be a pure sine wave. A comparison of the method used to obtain Figure 265 with the method of deriving the sine curve will show this clearly.

Figure 265 shows us graphically both ways in which the line has affected the propagation of our wave. The decrease in the height of each successive cycle illustrates the "attenuation" of the current. Now the fact that we have a succession of cycles plotted against distance instead of time shows us how there has been established by the medium a definite speed of propagation. For the particular frequency there is a definite length, viz., 12, which as expressed here is the number of sections for one complete wave. We may call this wave length $\lambda$, and there is a definite relation between $\lambda$ and $\beta$ which is given as follows:

$$\lambda = \frac{2\pi}{\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (93)$$

since $\beta$ is a constant for the line at a given frequency and is a measure of the amount of "phase shift" per section, and when obtained from equation (88) will be on the basis of radian measure. In other words, there are 360 degrees or $2\pi$ radians in one wave length (or one cycle) $\lambda$. For the particular network we are discussing, then this becomes

$$\frac{2\pi}{\beta} = 12 \times 18\tfrac{3}{4} = 225, \text{ or } \lambda = \frac{6.28}{225} = 0.0279 \text{ radians per mile.}$$

Now, we know that if an E.M.F. has a frequency of f cycles per second it sends out f waves in a second, and since we can determine the length of each wave, we can compute the speed with which these electric waves travel by the relationship—

Velocity = Frequency x Wave length

It can thus be seen that the speed of electric propagation depends upon the properties of the circuit considered and also upon the frequency, since the wave length depends on $\beta$, the wave-length constant, and the value of this in turn depends upon the circuit constants and the frequency.

Summarizing all the foregoing facts in this Article, we have for our transmission line—

a. Both current and voltage are retarded.

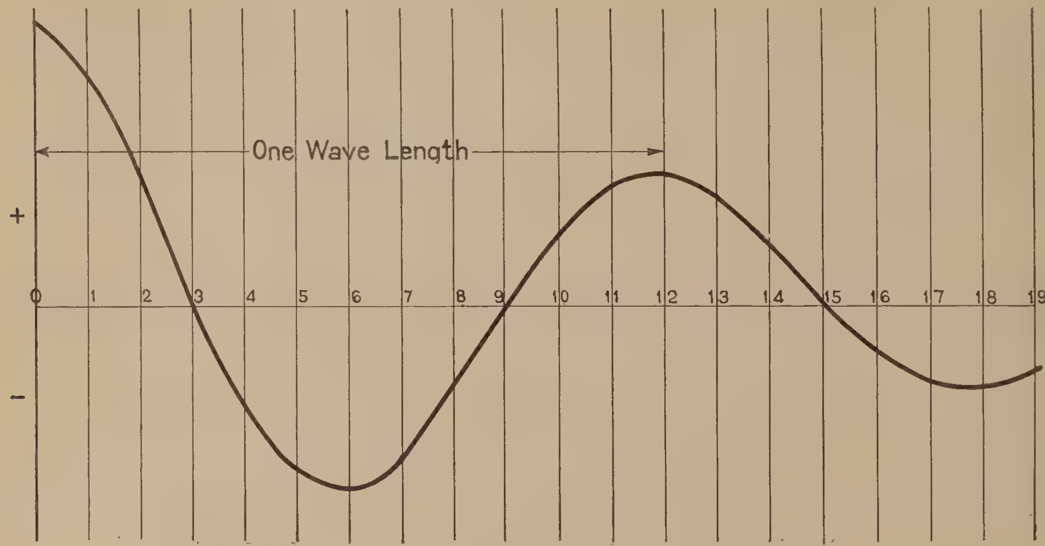



*Fig. 265—Current Wave Along Typical Transmission Line.*

b. Both current and voltage are attenuated.

c. The amount of attenuation and the amount of "slowing down" are determined by the physical properties of the circuit and by the frequency of the applied voltage.

Accordingly, since power is proportional to the product of E and I, we should expect that the power would decrease faster than either voltage or current, and such is actually the case as illustrated by Figure 266. Here the magnitudes of voltage and current are plotted against distance, and the power, $P = EI \cos \Theta$ is similarly charted.

Expressed mathematically, $I_n = I_o \epsilon^{-n\alpha}$ and $E_n = E_o \epsilon^{-n\alpha}$ and, therefore $P_n = E_n I_n \cos \Theta = E_o I_o \epsilon^{-2n\alpha} \cos \Theta$ ............................ (94)

### 121. Reflection and Transition Loss

We have said that it is a characteristic of wave motion that in passing from one medium to another, a certain amount of the energy propagated by the wave is lost. For instance, light waves striking a pane of glass, water, or some denser medium are transmitted through in part but a certain amount is reflected. The amount of energy reflected depends on the physical properties of the media

through which the wave motion passes; the greater the dissimilarity, the greater the reflection. We may consider that such reflection is due to the different velocities with which the dissimilar media propagate energy, so that at the junction some interaction takes place, the result of which produces reflection, i.e., a change in the amount of energy propagated.

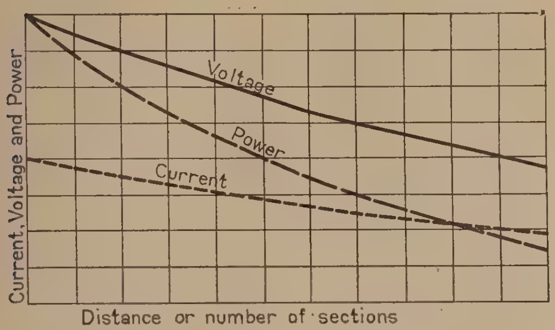



*Figure 266*

In transmitting electric waves, this reflection phenomenon is frequently met with, and it causes a "reflection loss". The amount of loss can actually be computed or measured, and if we take the case of two unequal impedances $Z_1$ and $Z_2$ the ratio of power received to the power that would be received on a smooth circuit ($Z_1 = Z_2$) is given by

$$\frac{P_2}{P_1} = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \times \frac{\cos \Theta_2}{\cos \Theta_1} \quad \ldots\ldots *(95)$$

*In practical telephone work the factor $\frac{\cos \Theta_2}{\cos \Theta_1}$ is usually neglected, due to the fact that on the ordinary connection, substation to substation, this factor cancels out when considering the total reflection loss on the circuit.

where $Z_1$ is one vector impedance with an angle $\Theta_1$, $Z_2$ is the other vector impedance with an angle $\Theta_2$, and the direction of propagation is from $Z_1$ to $Z_2$. If it is remembered that reflection loss is a reduction in energy which is met with in all forms of wave motion, a clearer conception of this phenomenon is obtained.

There is another so-called loss met with in transmission work which is known as the "transition loss". In the preceding Chapter we learned that if the load resistance was not equal to the resistance of the system to which it was connected, the power received by the load would not be a maximum. Similarly, in A.C. circuits certain conditions must be met in order that the load may receive maximum power. Briefly stated, this condition is that **the resistance of the load must equal the resistance of the generator and the reactance of the load must be of the same magnitude as the reactance of the generator but of opposite sign.** When these conditions prevail the two reactance components will cancel one another so that the circuit will behave as a D.C. circuit. It naturally follows that the resistance components must follow the D.C. law given in Chapter XIX. The transition loss, so-called is in effect a comparison of the power that is received by a load under any given circuit conditions with the power that could be received if conditions permitted the maximum transfer of power. Usually this reduction in power is given in the form of a ratio in the same way that the reflection loss is given by a ratio. If we designate by $P_2$ the power that is actually received by the load and by $P_1$ the maximum power that could be received, the ratio of the two is given by

$$\frac{P_2}{P_1} = \frac{4R_1R_2}{(Z_1 + Z_2)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (96)$$

Transition loss is not a true physical loss, nor is it a measure of the efficiency of the circuit; it is merely an indication of what percentage of the maximum power possible of utilization is being utilized.

### 122. The Effect of Line Characteristics on Attenuation

In our branch of telephone service we are ever concerned with the most practicable manner of satisfactorily transmitting voice currents over great distances. Due to the very length of the circuits, undesirable attenuation and distortion effects which might not be serious in short circuits become deciding factors in determining whether or not intelligible conversation is possible.

The total attenuation at a given frequency from a talking subscriber's station to a listening subscriber's station (where no telephone repeaters are used) depends upon the length of the circuit, the attenuation per unit length, the energy transfer at the two ends of the circuit or at any junctions of dissimilar sections, and the energy losses due to apparatus that may be associated with the circuit. So closely related are the various losses that the "make up" of the circuit itself has either a direct or indirect bearing upon all of them. As for the length we would naturally expect that on a very long circuit the total loss would be so great that the energy reaching the distant end would be insufficient to operate the telephone receiver while such a condition would hardly be probable on a short circuit. Here we have a limitation from the energy standpoint which is peculiar only to long circuits.

Moreover, it should be remembered that while transmission of the required **volume of energy** is one essential, it is not the only consideration. If we refer to equation (87) we shall see that $\propto$ varies with the frequency f, i.e., currents of different frequencies may be attenuated unequally as they pass along the circuit. Thus it is not difficult to imagine a long circuit on which a frequency of 500 cycles is transmitted satisfactorily while a frequency of 1500 cycles is not. Under such conditions we would have a **distortion effect** and the longer the circuit the more serious this distortion becomes. Taking all such factors into consideration we find that there is a very complex relation between the physical characteristics of a telephone line, which determines its efficiency for satisfactory telephone transmission. First of all its length is an important factor as the overall attenuation varies directly with length. Second, the actual attenuation constant per unit length is a factor in the transmission of energy at any given frequency. Third, the extent to which this attenuation varies with variation in frequency has a direct bearing upon the distortion of the voice current or may impair the circuits **"quality"**; and fourth, apart from the circuit's efficiency as a transmitting medium we are concerned, from the standpoint of power transfer, telephone repeater operation, etc., with its characteristic impedance as given by equation (82), that is—

$$Z_o = \sqrt{\frac{z}{y}} = \sqrt[4]{\frac{r^2 + (6.28fl)^2}{g^2 + (6.28fc)^2}} \quad (82)$$

Now one of the solutions to the problem of long distance transmission has been the application of **line loading.** By such application we may make certain improvements in the circuit's transmission efficiency through one or more of the following effects:

a. A reduction of the circuit's attenuation per unit length.

b. A more even attenuation of the various frequencies within the band of frequencies to be transmitted, thereby reducing distortion.

c. A more nearly constant characteristic impedance for all frequencies within the band to be transmitted, a consideration which is most important in the satisfactory operation of telephone repeaters, but of some importance in considerations having to do with the circuit's termination.

### 123. Loading as a Means of Reducing Attenuation

The theory of loading is by no means simple and loading results are difficult to analyze through any physical portrayal. Perhaps the best conception that can be had of loading is a more or less mathematical one which can be gained from studying the effect of line characteristics on attenuation.

The equation given below is the general attenuation equation discussed in the preceding Chapter.

$$\propto = \sqrt{\tfrac{1}{2}\sqrt{[r^2 + (6.28fl)^2]\,[g^2 + 6.28fc)^2]} + \tfrac{1}{2}\,[gr - (6.28f)^2lc.]} \quad \ldots\ldots\ldots\ldots (87)$$

Here $\propto$ is the attenuation constant per unit length and the values r, g, l, and c are likewise given for one unit length of circuit. The practice of loading is merely a means of increasing the inductance, or factor **l** per unit length of circuit, and was first used in the long distance plant to reduce the attenuation. To appreciate fully this particular application let us now analyze equation (87), assuming that we have a typical open wire circuit such as was used in the early days of long distance telephony. The distance over which satisfactory transmission is possible on such a circuit is limited to a few hundred miles. If we desire to talk greater distances the first solution that might suggest itself lies in the reduction of **r** in equation (87). This means we must increase the size of the wires, thereby reducing the $RI^2$ losses in the circuit, but certainly this would be an expensive way of obtaining our objective since it would necessitate the use of more copper.

If we next consider some change in the value of the leakage, **g**, we will find that keeping the leakage to a minimum is advantageous because the lower the value of **g**, the lower will be the value of $\propto$, even with other line constants remaining unchanged. But here we find limitations because with the value of **g** reduced to zero, or with a condition of perfect insulation, we still have a too large value for $\propto$ due to the other constants of the line. Let us next consider the capacity per unit length appearing in the foregoing equation. Here we find that a reduction of **c** means a reduction of $\propto$, but on the other hand a reduction in capacity can be secured only by a wider separation of the wires, greatly reducing the number of circuits that might be carried on a single pole line and thereby considerably increasing the cost per circuit. As in the case of reduced resistance we might find any tangible results prohibitive on account of this increased cost.

There remains only to consider what effect will be obtained by changing the inductance, **l**, at the same time not ignoring the influence of r, g, and **c** upon the attenuation. That is to say, we know that it is good maintenance practice to keep the insulation of our circuits as high as possible, and we know that copper circuits are better talking conductors than iron circuits, and that 165 conductors permit us to talk over greater distances than 104 conductors due to their lower resistance; we know also that non-loaded cable due to its high capacity is a poor talking medium. But in the case of both **r** and **c** we have already found practical limitations, while in the special case of the value, **g**, it may be so reduced through proper maintenance that it can be neglected in equation (87).

With the leakage so low as to be neglected, or with $g = 0$, the attenuation equation becomes:

$$\propto \; = \; \sqrt{\tfrac{1}{2}\,(6.28fc)\,[\sqrt{r^2 + (6.28fl)^2} - 6.28fl]} \quad (97)$$

A study of this expression shows that within certain limits an increase in l will result in a reduced $\propto$. The improvement that can be obtained by increasing l will depend on the value of **r**; with **r** small but little decrease in $\propto$ can be effected by increasing **l**, while with **r** large, a substantial decrease can be effected, i.e., by "loading" the circuit with inductance we can reduce $\propto$, or expressing the same thing physically, we can reduce the energy loss in the circuit. However, inasmuch as any inductance we may add has resistance, we will by loading increase **r**, thus in some degree neutralizing our efforts to improve conditions. But with properly designed inductance units the increase in l more than offsets the increase in **r** so that the attenuation constant is reduced.

Before proceeding further with our analysis it will be well to consider the practicability of increasing the circuit inductance so as to obtain this reduction in energy loss. It will be remembered that equations (82) and (87) were developed on the assumption that the circuit properties, resistance, inductance, capacity, and leakage, were uniformly distributed. Theoretically therefore, in order to increase l we should find it necessary to increase the **distributed inductance** of the circuit, a difficult task. We could accomplish this by winding each conductor of the circuit with a spiral wrapping of iron wire or tape but the expense involved would be so great that only in special cases could this method be used.

In practice a solution is effected by supplying the loading inductance in the form of coils inserted in the circuit at regularly spaced intervals. We learned earlier that we may approximately simulate a circuit of distributed constants with a series of T-networks of lumped constants, and similarly the addition of inductance in "lumps" will produce the effect of increasing the distributed inductance provided that the "lumps" are sufficiently close together. Thus it is that a loaded circuit usually has load coils, which are nothing more or less than lumps of inductance, inserted at periodic intervals along the circuit, the interval depending on a number of factors but always small enough to obtain the effect of increased distributed inductance with its accompanying reduction in attenuation.

### 124. Loading to Reduce Distortion

Although we have succeeded in finding a means to reduce the energy loss in the circuit, we still have to consider the distortion effects. We must in any case be sure that the distortion effects have not been so exaggerated by loading as to counteract its benefits, and in modern practice we go further and employ loading to reduce distortion as well as attenuation. Accordingly, we shall develop certain simplified equations for impedance and attenuation of a non-loaded circuit and then develop similar expressions for this same circuit when loaded.

Since non-loaded cable circuits have the greatest loss and greatest distortion we shall analyze this type of facility. The leakage **g**, of cable is so small that it may be assumed negligible and due to the very small separation between the wires, the inductance is likewise small enough to be neglected. For the non-loaded cable, therefore, where $l = O$, and $g = O$, the expressions for impedance and attenuation become—

$$Z_o = \sqrt[4]{\frac{r^2}{(2\pi fc)^2}} = \sqrt{\frac{r}{2\pi fc}}$$

and $\propto \; = \sqrt{3.14\ fcr}$ .................... (98)

Now since $Z_o$ is a vector quantity it must have associated with it an angle. The term $2\pi fc$ gives to the expression under the radical an angle of -90°, which becomes one-half as great when taken from under the radical, so that the complete definition of $Z_o$ is—

$$Z_o = \sqrt{\frac{r}{2\pi fc}},\ \Theta = -45^\circ \quad \ldots\ldots \quad (99)$$

From these two equations we see that both the attenuation and the impedance vary with frequency, and consequently there will be distortion effects, as mentioned earlier.

Now we will assume that we load this cable circuit. As before **g** may be neglected but by increasing **l** we have made the reactance $2\pi fl$ very large, so large in fact that we may now consider **r** insignificant as compared with $2\pi fl$. Developing the impedance and attenuation equations on this basis we obtain—

$$Z_o = \sqrt{\frac{L}{C}} \text{ (approximately) } \ldots (100)^*$$

$$\propto = \sqrt{\frac{R^2C}{4L}} \text{ (approximately) } \ldots (101)^*$$

Here we see that $Z_o$, since it contains neither inductive nor capacity reactance, has no angle, i.e., $\Theta = 0^\circ$, or what amounts to the same thing, the impedance is perfectly constant and independent of the frequency. Likewise $\propto$, the attenuation constant, is independent of frequency. Thus by loading the circuit we have not only reduced the energy loss but have further improved conditions by eliminating distortion effects.

The above expresses mathematically the results of loading. It will be more difficult to obtain a physical picture of these results, but let us first consider the effect of the increased inductance on the characteristic impedance. The load coils connected in series with the line wires naturally increase the impedance and at the same time they neutralize the effect of the capacity inherent to the circuit, but not so simply as in the case of a single inductance in series with a condenser. Nevertheless, we may consider the loaded circuit as made up of a number of sections consisting of **series** inductance and capacity, each section acted upon by the voltage set up across the capacity of the preceding section. This results in an increased voltage and a decreased current, as well as practically eliminating the phase angle of the characteristic impedance. Now due to the increase in the impedance of the circuit, or due to the power transmitted being in the form of higher voltage and less current, the $RI^2$ losses are consequently less and the total energy loss must inevitably be less. This is a means of higher voltaged energy transmission for the reduction of power losses, and is applicable to high frequency transmission which could not merely employ step-up and step-down transformers as described in Article No. 100. Viewed from an energy standpoint, it is obvious that if a loaded circuit receives the same amount of energy as a non-loaded circuit the energy transmitted over the loaded circuit will be greater because its losses are less. Actually, the losses are so much reduced that notwithstanding the fact that the entering current may be less (due to $I = \frac{E}{Z_o}$) the received current on a loaded circuit is greater than that on a non-loaded circuit of the same length, providing that this length is of appreciable magnitude.*

*Unit length is now taken as one "loading section", the distance between two adjacent coils.

The next important aspect of loading which we might discuss is the spacing of the coils. It was stated above that these coils must be close enough together so that the effect of distributed inductance will be obtained. For a proper appreciation of this condition let us simulate a uniformly loaded line with a multisection uniform network. Now it must be remembered that the circuit properties, inductance and capacity, produce reactions which vary with **frequency;** capacity reactance decreases and inductive reactance increases as the frequency becomes greater. While it is equally true that this same frequency effect takes place on the simulating network, the lumping of the inductance and capacity exaggerates the effect.

On the uniform line, current passes from the positive voltaged wire to the negative voltaged wire continuously through the small capacity elements distributed along the circuit, whereas on the network this passage of current can take place only at the middle of the T-sections. Thus, the inductive effect in the network will be somewhat greater than that in the uniform line due to the larger current traversing the inductances, while the capacity effect will accordingly be less. Now of course, the greater the number of sections in the network the less will be the difference in behavior of the line and the network. But since any difference is exaggerated with increased frequency, any network analysis of a uniform line really resolves itself into a determination of how many sections shall be taken in order that the simulation of the line by the multisection network may be satisfactory over a **given frequency range.** Similarly, on loaded circuits, the coil spacing (which in effect merely defines the length of each section of the multisection network) is so chosen that the change produced by frequency, **over a given range,** does not differ greatly from the effect that would be produced on a continuously loaded circuit of about the same average constants, r, l, g, and c. It should be noted, however, that either the value of the loading inductance will be a factor in determining the spacing since its inductance will be a part of the simulating network, or any chosen standard spacing will be a factor in determining the inductance values the coils may have.

### 125. The Cut-Off or Critical Frequency

We have learned that the band of frequencies between about 200 and 2,000 cycles will transmit telephone conversations without any considerable

*On very short circuits it is possible to **decrease** the efficiency by loading. The explanation lies in the fact that the increased $Z_o$ overcomes the effect of the reduced $\propto$.

distortion, and loaded circuits accordingly are designed with a view to transmitting at least this band. The lump loaded circuit simulates a smooth circuit having a correspondingly larger series inductance very closely over a considerable portion of this band, but towards the upper range the simulation becomes less exact. In other words, whereas a smooth circuit would have an impedance and attenuation constant which might vary but little with change in frequency, the network, i.e., the loaded circuit, has an impedance and an attenuation constant which generally increase with frequencies near the upper limit of the 200 to 2,000 cycle band. It is quite possible, however, to extend this range by changing the design of the loading, and the #19 gauge H-44-25 loaded circuit is a most interesting illustration of what can be accomplished in this way. For many types of loading, however, the circuit design is such that the essential frequencies only are transmitted, and a marked increase in both impedance and attenuation takes place above this band. In fact, the attenuation rises so rapidly that only a few hundred cycles above the upper limit of the band the amount of current that can be sent through is practically negligible and the circuit is said to "cut off". This critical frequency at which "cut-off" occurs is dependent only on the inductance and capacity per loading section and is determined from the expression—

$$f_C = \frac{1000}{\pi\sqrt{L_oC_o}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (102)$$

where $L_o$ and $C_o$ are the inductance and capacity values of the equivalent network and are approximately the actual inductance and capacity values of the loading section. They are expressed in henrys and microfarads, respectively.

### 126. The Effect of Loading Upon the Wave-Length Constant

Up to this time we have said little about the wave-length constant of a loaded circuit, but knowing from our analysis in the preceding Chapter that increased inductance introduces a retarding effect on voltage and current, we would expect the wave-length, $\lambda$, to be decreased. That is since

$$\text{Velocity} = \text{Frequency x Wave-Length}$$

$$\text{Velocity} = W = f\,\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (103)$$

we see that, with f constant, any reduction in W must be due to a decrease in $\lambda$. Now in a loaded circuit where we may assume **r** and g negligible, the value of $\beta$ obtained by simplifying equation (88) is given by—

$$\beta = 6.28f\,\frac{\sqrt{L_oC_o}}{1000} = 2\pi f\,\frac{\sqrt{L_oC_o}}{1000} \quad \ldots\ldots \quad (104)$$

and since

$$\lambda = \frac{2\pi}{\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (93)$$

we have

$$W = f\lambda = \frac{2\pi f}{\beta} = \frac{1000}{\sqrt{L_oC_o}} \text{ “loads” per second} \ldots (105)*$$

A casual glance at equations (102) and (105) suggests that they are related and such is actually the case.

### 127. Mechanical Analogy of Loading

Though the physical concept of loading apart from the mathematical analysis of the various formulas may be a difficult one, let us consider a mechanical analogy which will illustrate not only the effect of reduced attenuation but the critical frequency and reduced velocity phenomena as well. We will recall that telephone transmission is a problem dealing with wave propagation and as such is subject to all the laws of that phenomenon. Accordingly, let us for the purpose of observing some of these laws consider the propagation of a wave along a string.

Figure 267 shows mechanical wave motion being propagated along a stretched string where the energy is supplied by the vibration of a tuning fork. As we proceed along the string the wave seems to die out. Now, within certain limits if we should substitute for the string a heavier one we should find that the wave is propagated farther or is less attenuated, as illustrated by Figure 267-B. Here **inertia** which is analogous to inductance has reduced the **attenuation** and it can also be demonstrated that the velocity of the moving wave is lowered. Let us carry our experiment a little further and see if it is possible by adding inertia at some one point to assist the propagation. Let us assume that instead of using a heavier string we have placed a weight in the middle of the lighter string, making the string and weight together as heavy as the string of Figure 267-B. Here we find that the single weight has not assisted us in reducing the attenuation of the wave which dies out in almost the same way as previously until the weight is reached and there the wave seems to stop altogether. If instead of the heavy weight in the center of the string we now repeat our experiment with a few scattered weights we shall still find that the wave will not pass the first weight. On the other hand, if we use tiny weights equally spaced along the string, in fact so many that **several such weights appear in each wave-length,** as in Figure 267-D we shall find that we now get the same effect as with the heavier string. In other words, this "loading" has reduced the attenuation and the wave seems to extend as far over the light string equipped with the tiny equally spaced weights as over the heavier string having uniformly distributed inertia.

*Here W will be in "loads" per second because the unit length for which $\beta$ is determined is one loading section.

From this behavior of the loaded string, we may safely conclude that on a loaded circuit the loading coils must be so spaced that there are several in each wave-length of any frequency we wish to transmit. Now since the wave-length varies with $\beta$ and hence with the frequency, it naturally follows that loading suitable for the transmission of, say, 1,000 cycles is not necessarily adapted for the transmission of 3,000 cycles, because at 3,000 cycles the wave-length will be considerably shorter than at 1,000 cycles. Accordingly the number of loads per wave-length is reduced and the load coil, far from aiding transmission hinders it, just as the single heavy weight hinders "transmission". In other words, the velocity of a wave for any frequency we wish to send along the circuit must be large enough so that several* coils are passed over in each wave-length. If the proper number is not encountered, the losses increase rapidly and "cut-off" follows.

minimum resistance in the winding and minimum losses in its core. Furthermore, coils installed in open wire circuits are subject to lightning hazards

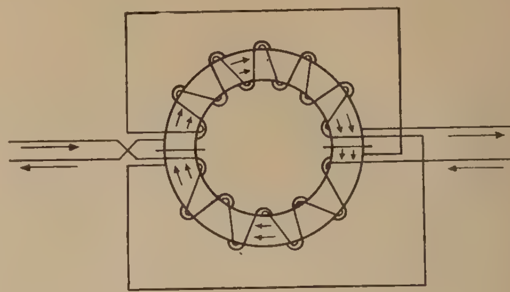


*Figure 268*

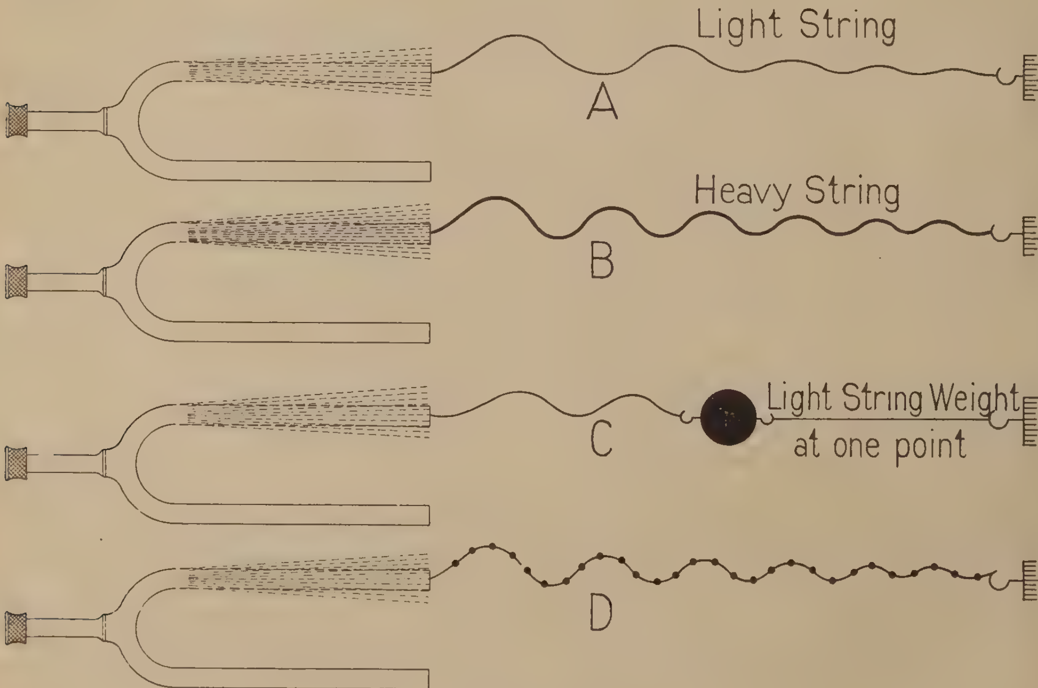



*Figure 267*

**128. Features in Loading Coil Design**

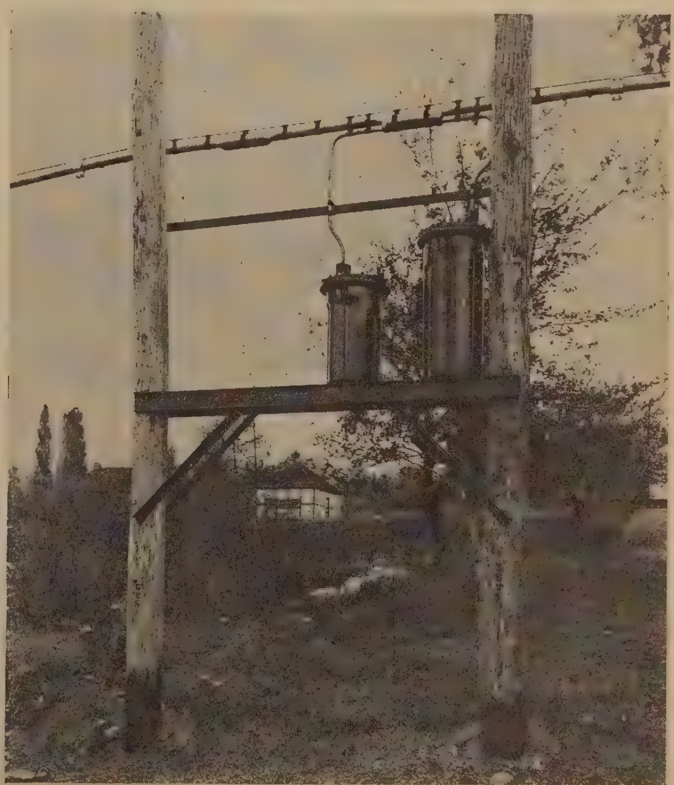
In the design and manufacture of the various types of loading coils used on long distance lines there are a number of requirements other than merely providing a specified inductance value. As stated previously, loading is effective in reducing attenuation only when the increase in the alternating current resistance of the circuit is held within certain limits. A loading coil should, therefore, have and must be highly insulated,—in fact an insulation test of 8,000 volts is given each open wire coil before it leaves the factory. Each coil's inductance must be accurately divided into two parts so that one-half of the inductance is inserted in one wire of a talking circuit and the other half is inserted in the other wire, thereby maintaining circuit balance. This requirement is a very exacting one and unless the two windings of each coil are identical in every respect crosstalk or noise will result. Figure 268 illustrates the method of winding open wire loading coils to give a high degree of balance.

*In practice, about nine coils must be encountered in each wave-length.

## LOADING

*Above*—Types of iron-core loading coils.

*Left*—Underground cable manhole showing method of installing loading pots.



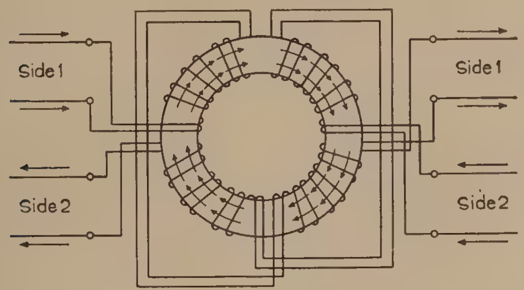
*Right*—Standard method of mounting aerial cable loading pots.

The loading coil core for open wire types consists of a toroid of a special grade of very fine iron wire having a coating of lacquer. A gap is sawed in the core to prevent permanent magnetization. Some types of cable coils employ a special core compound containing powdered iron which is pressed into solid rings. These coils are said to have a high degree of "magnetic stability". More recently, **permalloy** has come into use for loading coil cores, the material being first powdered and then pressed into rings. Because of its remarkable magnetic properties, loading coils with permalloy cores are only about 1/3 as large as the former standard iron—core coils.

d. Loading coil protection should be well maintained to prevent permanent magnetization or other damage by lightning.

e. To prevent loading coil magnetization the line current used for telegraph or other operation should not exceed the specified limits for the particular type of loading (open wire limit is 100 milamperes.)

f. It is practicable to load the side circuits of a phantom group without loading the phantom or to load the phantom without loading the side circuits, but one side circuit can not be loaded without the other.



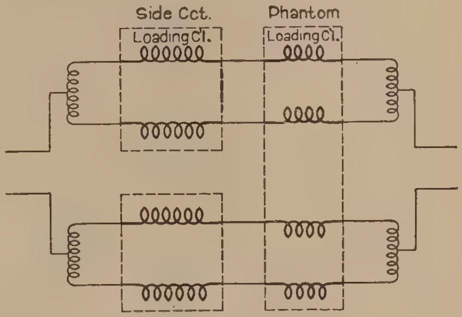




*Figure 269*

All loading coils are potted in suitable cast iron cases. For open wire installations they are potted either singly, or in groups of three for phantom circuits. For cable loading a large number of coils may be potted in a single but much larger case and are so arranged as to prevent crosstalk.

Coils for phantom loading usually have lower inductance values than side circuit coils but must, of course, have four windings. Figure 269-A illustrates the windings of a phantom loading coil and Figure 269-B illustrates the connections of a single loading point in a phantom group where both the side circuits and the phantom are loaded.

### 129. Important Considerations in Loading Practices

There is a great deal to be said about the proper use, installation, and maintenance of loading coils in the plant which cannot be covered here but will be found in the Company's standing instructions. A few important considerations, however, are fundamental and should be remembered:

a. In connecting a loading coil, care should be exercised to prevent a reversal of one winding thereby neutralizing the coil's inductance.

b. The inductance values of loading coils should be kept within 2% where the circuit is used in connection with telephone repeaters.

c. The loading coil spacing should be accurate to within 2% where the circuit is used in connection with telephone repeaters.

g. Loading is only effective when the line insulation or factor **g** is kept within proper limits The curves shown in Figure 270 illustrate the importance of good insulation on loaded circuits. It will be seen that the attenuation or transmission loss increases more rapidly with lower insulation on loaded than on non-loaded circuits, and as can be seen by the crossing of the curves there are certain low insulation values where loading is a transmission detriment.

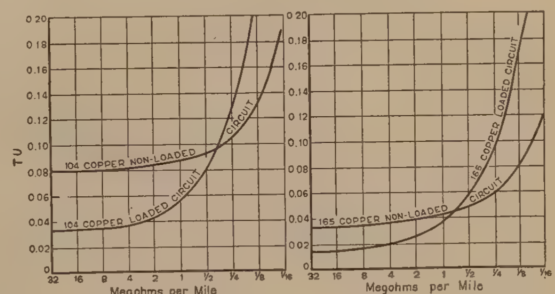



*Fig. 270—Effects of Low Insulation upon Attenuation of Open Wire Circuits.*

h. The sending or receiving end impedance of a loaded circuit depends largely upon the termination of the circuit, i.e., whether terminated at a half-section point, .2 section point, mid-coil point, etc., and will not necessarily be the same

as the characteristic impedance due to the form of termination. (This will be covered more thoroughly under "Use of Telephone Repeaters).

### 130. Building-out Condensers

On account of the actual conditions encountered in the field it is not always possible to effect uniform spacing of loading coils. Due to line changes, intermediate submarine or toll entrance cable, loops into testing stations, etc., a loading section may be either too long or too short. This is usually corrected by the use of building-out condensers of properly designed capacity values. In the case of a short section the addition of the condenser without other changes will correct the irregularity. In the case of a long section it is necessary to create an additional loading point, retranspose the circuits, and install building-out condensers in the remaining short section.

The capacity value of the building-out condenser is not exactly that obtained by multiplying the length of circuit by which the section is short by the capacity per mile but is given by the formula—

$$C_b = C_o - lc \quad \ldots\ldots\ldots\ldots \quad (106)$$

where $C_b$ is the building-out capacity, l is the length of the short section, c is the capacity per mile, and $C_o$ is the average **equivalent** capacity per loading section or, in effect, the "lumped" capacity that would simulate the distributed capacity of a section.

In the case of a phantom group, six condensers connected as shown in Figure 271 are required for building out the group. Their values can be calculated from the equations—

$$A = \tfrac{1}{4} C_{bp} \quad \ldots\ldots\ldots\ldots \quad (107)$$

and $$B = C_{bs} - A \quad \ldots\ldots\ldots\ldots \quad (108)$$

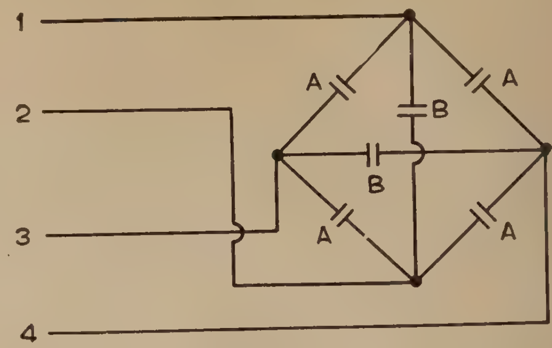



*Figure 271*

where $C_{bs}$ is the building-out capacity of the side circuit and $C_{bp}$ is the building-out capacity of the phantom. Where the phantom circuit only is loaded it is not possible to build-out the phantom without at the same time building-out the sides.

In building out loading sections in cables it is usually more economical to obtain the required additional capacity by the use of a stub cable than by means of specially designed condensers as discussed above. The needed additional capacity is secured by bridging the stub cable, which is deliberately designed to have abnormally high capacity, on the main cable at some convenient point in the short section. It is, of course, necessary that the conductors of the stub cable be free from electrical defects and capacity unbalance.

CHAPTER XXII

# TRANSMISSION UNITS AND MEASUREMENTS

## 131. Units for the Measurement of Transmission Losses and Gains

As in dealing with any other quantity, we require some unit of measurement when dealing with the energy losses due to attenuation in the transmission of human speech or in the transmission of any alternating current from a sending device to a receiving device over a long line or through complicated circuits. Without some such unit we would be handicapped in giving any scientific expression to the grade of telephone transmission under various conditions. It would be natural for us to say that sufficient energy had been transmitted from the speaking station to the listening station for the listener to hear distinctly every spoken word, or to say that the sound coming from the receiver at the receiving station was so faint as not to be intelligible, but this would be a crude method of comparison. For the same reason that we need some adopted standard as a unit of length such as the foot or the meter to measure distance, we require some standard for the measurement of transmission loss or transmission gain in telephone work.

Until quite recently the unit used for this purpose was the "standard cable mile". This represented the loss due to one mile of an old type of standard #19 gauge cable, having a resistance of 88 ohms per loop mile and a capacity of .054 mf. per mile. This unit was employed in connection with a standard reference circuit, consisting of two standard common battery substation sets connected through two 25-A repeating coils to an adjustable length of artificial cable, each unit of the artificial cable representing or closely approximating the makeup of the standard cable. The substation sets of the standard reference circuit used #229 standard transmitters, #122 standard receivers, #20 standard induction coils, and 2 mf. condensers. Twenty-four volt battery supply was furnished to the transmitter through the windings of the 25-A repeating coil to which the sets were connected. Figure 272 shows the circuit connections of this standard reference circuit arranged for making a comparison test.

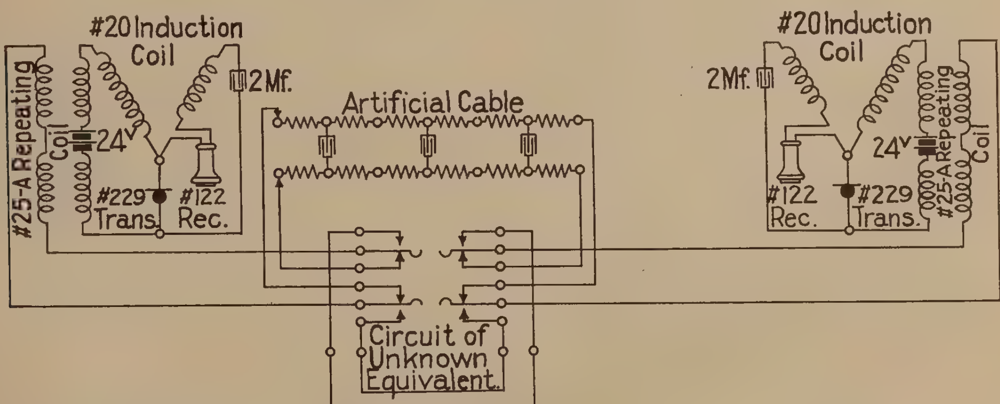



*Fig. 272—Reference Circuit Arranged for Making Transmission Measurements.*

Transmission measurements were made with the standard reference circuit by talking over the line or circuit which was under test, and comparing the volume of speech received under that condition with that received when talking over the artificial cable. As the artificial cable was designed to permit changing the number of units, the test was made by switching from the circuit under test to the cable and making comparisons of the volume of sound in the two cases. With the number of miles of standard cable so adjusted as to give no essential difference in volume over the two circuits, the circuit under test was said to have a transmission equivalent or loss equal to that number of miles of standard cable.

In the standard cable unit the series inductance and the shunt leakage were negligible while the bridged capacity of .054 mf. was appreciable. This unit, therefore, attenuated the various frequencies that make up the band for telephone transmission unequally, attenuating the higher frequencies more than the lower frequencies. To illustrate, the attenuation constant $\alpha$ was equal to .109 for 800 cycles frequency and .122 for 1000 cycles frequency, etc.

This meant that the percentage reduction in power caused by inserting a mile of standard cable between a sending and receiving element was different for different frequencies, which was not particularly serious as long as the unit was used only in making comparisons by talking tests such as that

described above. But when it became desirable to make more accurate transmission measurements than that method permitted, using only a single frequency, the unit had serious disadvantages. Under these conditions, to say that a telephone circuit had an equivalent of a certain number of miles of standard cable was largely meaningless unless the frequency at which the equivalent was computed or measured was stated at the same time. This inconvenience was obviated to a degree by the adoption of a standard frequency of 800 cycles, which it was thought was more nearly representative of the average voice range than any other single frequency. With this convention, it was understood that the loss at a frequency of 800 cycles was meant when equivalents were given in standard cable miles. But later investigations indicated that a frequency of 1000 cycles was more nearly representative of the average voice range than 800 cycles. So a condition was reached where transmission measurements and computations were made with a frequency of 1000 cycles but the unit used was the standard cable mile at 800 cycles.

This rather confusing situation led to the dropping of the mile of standard cable altogether as a unit of measurement and the substitution of an arbitrarily selected unit not differing greatly in magnitude from the standard cable mile through the voice range, but having exactly the same significance at any and all frequencies. That is to say, **the new unit, called the TU, represents always a fixed percentage reduction in power no matter what frequency is involved.** Its magnitude may perhaps be best grasped by remembering that in a circuit equating to ten TU the output power will always be 1/10 of the input power. Mathematically, the power ratio for **one TU** may be expressed as

$$\frac{P_I}{P_O} = 10^{.1} \quad \ldots\ldots\ldots\ldots \quad (109)$$

where $P_I$ is input power and $P_O$ is output power. This corresponds to a current ratio of $10^{.05}$ and to an attenuation constant value of $\propto = .115$.

Table XIV showing the power ratios for several values of transmission units (TU) will aid in forming a clear conception of the magnitude of the unit.

For any given power ratio the number of TU corresponding can be determined by the following simple formula—

$$\text{No. of TU} = N = 10 \log \frac{P_I}{P_O} \quad \ldots\ldots \quad (110)$$

or if the current ratio rather than the power ratio is known

$$N = 20 \log \frac{I_I}{I_O} \quad \ldots\ldots\ldots\ldots \quad (111)$$

or from equation (*72*)

$$N = 20 \log \frac{I_I}{I_O} = 20 \log \epsilon^{\propto} = 20 \times \propto \times \log \epsilon$$

$$= 20 \times .434 \times \propto = 8.68 \propto \quad \ldots\ldots \quad (112)$$

It may be noted that for $N = 1$, the last equation gives us the value for $\propto$ noted above, namely $\propto = .115 = \frac{1}{8.68}$. The loss represented by one TU is identical with the loss represented by one mile of standard cable at the one frequency of 890 cycles,

TABLE XIV

RELATION BETWEEN TRANSMISSION UNITS (TU) AND POWER RATIOS FOR GAINS AND LOSSES

| Transmission Units | Approximate Power Ratio | | |
|---|---|---|---|
| | For Losses | | For Gains |
| | Fractional | Decimal | Decimal |
| 1 | 4/5 | .8 | 1.25 |
| 2 | 2/3 | .63 | 1.6 |
| 3 | 1/2 | .5 | 2.0 |
| 4 | 2/5 | .4 | 2.5 |
| 5 | 1/3 | .32 | 3.2 |
| 6 | 1/4 | .25 | 4.0 |
| 7 | 1/5 | .2 | 5.0 |
| 8 | 1/6 | .16 | 6.0 |
| 9 | 1/8 | .125 | 8.0 |
| 10 | 1/10 | .1 | 10.0 |
| 20 | 1/100 | .01 | 100.0 |
| 30 | 1/1000 | .001 | 1000.0 |

since at this and only this frequency the attenuation constant for the mile of standard cable is also .115.

There is also a standard reference circuit, called the "Transmission Reference System" for use with the TU. The purpose and principle of this circuit is the same as that of the former standard reference circuit already discussed. It is, however, considerably different in design being distortionless from sound input to the transmitter to sound output from the receiver. The circuit is so arranged that it causes the same net loss, sound input to sound output, with 24 TU in its artificial line as did the old reference system with 24 miles of standard cable in its artificial line. This adjustment was made so that the quantitative standards for good telephone transmission would not have to be radically revised when the change from the standard cable mile to the TU was made. Thus, while the TU avoids the faults of the former standard unit, it is so near it in magnitude that no widely different conceptions of transmission quantities were involved in its adoption.

Although we have been considering the transmission unit (TU) entirely in connection with measurements of "loss" or "attenuation", it is equally useful in the measurement of "gain" such as that given by a telephone repeater. A telephone repeater would be said to have a gain of so many TU if the circuit in connection with which it were used was effectively shortened or had its attenuation reduced to that extent.

### 132. Transmission Measurements

Although the apparatus used in making transmission measurements is somewhat complex, this is due entirely to the difficulties inherent in the measuring of high frequency currents of low value, and not in any way to the theory involved. The most obvious way of determining the attenuation of a circuit is to measure the currents sent and received at the two terminals, and thus learn the value of the current ratio, from which the attenuation may be determined. However, this method does not lend itself to rapid work and for routine measurements the transmission measuring sets, 3-B, 6-A and 4-B, reading directly in TU are much more suitable. The general arrangement of these sets in making transmission measurements is illustrated by Figure 273. The set is first calibrated by connecting a voltage to a fixed artificial line which causes a definite known loss corresponding to a certain current ratio. The entering current, after passing through this line, is amplified and rectified and passes through a potentiometer by means of which a D.C. meter may be made to give any desired deflection, usually mid-scale. After calibrating, connections are changed so that the same voltage is applied to a variable artificial line in series with the circuit whose equivalent is to be determined. By **cutting out** sections of the artificial line the total loss in the circuit is made the same as that in the calibrating circuit, so that the D.C. meter gives mid-scale deflection in both cases. The dials are arranged to read the loss in the "unknown" circuit directly. This is accomplished by constructing the variable artificial line to cause a maximum loss exactly equal to the loss caused by the fixed artificial line. When the measuring dials are set at zero, the variable line will cause the maximum loss; with the dials set at 10 TU, the total loss caused by the variable line will be the maximum minus 10, and so on.

Considering the component parts of the complete circuit, we have a generator or sending element, a load or receiving element, and a line connecting the two which may be the calibrating standard or the circuit under test, depending upon the position of

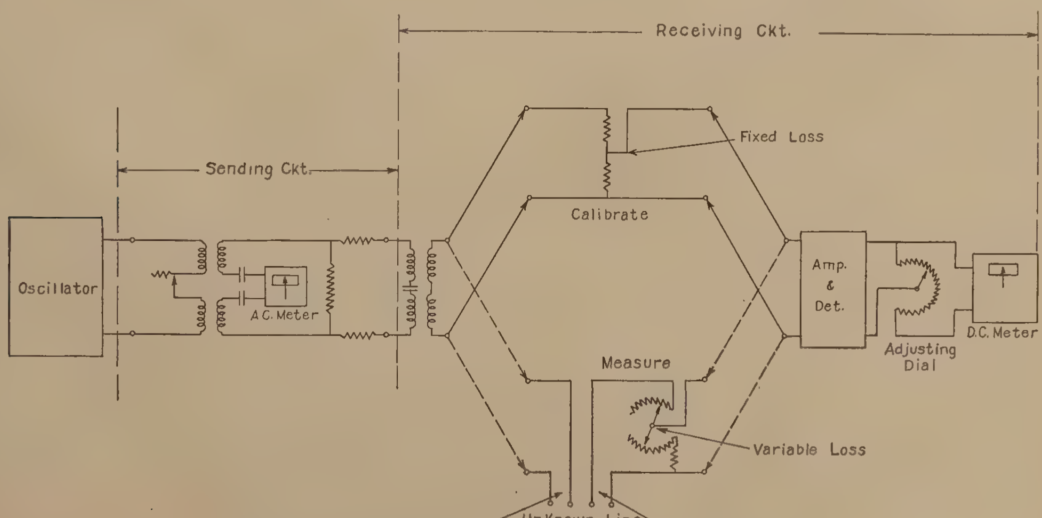



*Fig. 273—Principle of Transmission Measuring Set.*

the switching key. In order that any reflection losses on the connection may be reduced, there are associated with the sending and receiving elements variable networks which may be adjusted to have impedance values closely approximating those of the circuits to which the elements are connected. Also, in order that line noises caused by inductive effects may not appreciably impair the accuracy of the readings a filter which absorbs all currents except those between 850 and 1150 cycles is connected in the receiving element. It is obvious that noise will cause an error inasmuch as it increases the received energy and the ratio of energy received to energy sent will be in error.

Since all artificial lines, networks, etc. in this apparatus are made up of resistances it is possible to make measurements with them at any desired frequency in the telephone band. A study of the equivalents of the majority of circuits measured at a single frequency and measured with a band of talking frequencies for comparison has led to the standardization of 1,000 cycles for tests of this nature, however, as this particular single frequency will give for the various conditions, results most closely approximating the talking equivalents. This does not mean that measurements are not sometimes made at other frequencies. The transmission measuring set is often employed in the study of a circuit's "quality" by making measurements over the entire voice frequency band and charting the "loss-frequency" curves, the filter being cut out when such measurements are made. These together with "gain-frequency" curves will be discussed in later articles, but at this point there are certain other features of the transmission measuring set to be discussed.

The 4-B and 6-A transmission measuring sets are adapted to permanent office installations. The testing circuit of the former terminates in two cords for the sending and receiving connections, respectively, with a reversing key to send and receive in either direction without interchanging the cords. The testing circuit of the 6-A set does not differ in essential respects. The set, being relay rack mounted, however, is terminated in jacks for patching to the circuits to be tested rather than in cords as in the case of the 4-B set. Trunks are usually installed between the transmission measuring set and the testboard and between the transmission measuring set and the toll switchboard. These trunks terminate in jacks at the set and may be picked up by the testing cords. A talking circuit is also provided at the measuring set and may be used to talk over a circuit connection to the trunks or over a call circuit to a test operator in the toll operating room. The 3-B transmission measuring unit is a portable set which can be conveniently used for measuring the transmission equivalents of cord circuits, composite sets, switching trunks, and miscellaneous equipment units that affect the transmission features of a talking connection. It does not have the range of the 4-B measuring set but is compact and flexible and requires fewer batteries for its operation. It is equipped with binding posts and jacks suitable for making quick connections with any unit of apparatus to be measured. In its principle of operation it is not widely different from the 4-B set and accordingly will not be reviewed here.

In making tests with any of the sets over long toll circuits two methods are employed. One is known as the "straight-away" method, in which case there is a testing set located at each end of the circuit. A testing current of a given frequency and magnitude, determined by the accurately calibrated meters in the set, is delivered to the circuit by the sending element of one set and received by the receiving element of the other set. This permits a direct measurement of the circuit and does not require any calculations to determine the individual circuit's equivalent. The other method is known as the "loop test" and involves sending over one circuit and receiving on another, the two circuits being connected together at the distant terminal. In this case, the equivalent measured is naturally the sum of the equivalents of the two circuits and, as in the case of the Wheatstone bridge measurement of a single wire's resistance by the loop method, described in Article No. 39, it is necessary to employ at least three circuits, making loop combinations between them and setting up equations for these loop values. Perhaps the simplest method of calculating the equivalent of any one circuit is as follows:

a. Measure the loop equivalent of circuits A and B.

b. Measure the loop equivalent of circuits B and C.

c. Measure the loop equivalent of circuits A and C.

Add together the three loop equivalents and the sum will be twice the total equivalent for the three circuits. Divide by two and the value obtained should represent the sum of the individual equivalents for the three circuits. Subtract from this value any one of the above measurements and the difference will represent the equivalent of the circuit not included in that particular measurement.

The general theory involved in the transmission measuring sets discussed above is also utilized in the #2-D repeater gain set, except that when measuring gains, instead of cutting out loss in series with the unknown circuit an additional loss is connected in series with the unknown circuit so that the dial readings show a gain in TU instead of a loss.

### 133. Characteristics of Standard Telephone Circuits

In the telephone plant we have a great variety of circuits differing widely in their electrical properties or in their characteristics relative to the transmission of speech. First, we have the open wire circuits using either standard 104, 128 or 165 copper wire as conductors. These may be either loaded or non-loaded regardless of whether the actual talking connection is over a phantom or a

side circuit. Second, we have toll cable circuits made up of cable conductors either of 10, 13, 16 or 19 A.W.G. conductors. Cable circuits may likewise be either loaded or non-loaded with both side and phantom talking circuits, but unlike open wire may in some cases employ four conductors instead of two conductors as a single talking circuit. There is a third class of toll line circuits we may call "miscellaneous", and it includes carrier current channels, radio circuits, single conductor grounded submarine cable circuits, etc. The circuits in this third class will not be considered here on account of their special nature, but we shall take up the various kinds of circuits that are more common.

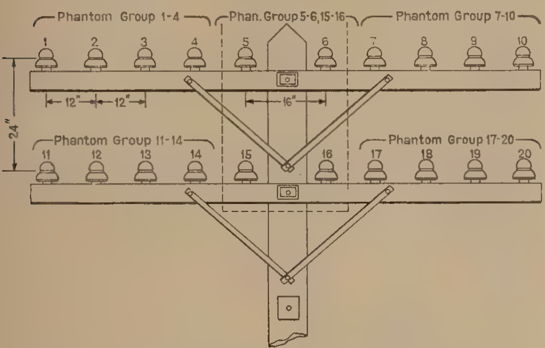



*Fig. 274—Ideal Phantom Group Arrangement for 20-Wire Line.*

Figure 274 shows a pole and crossarm diagram of a 20-wire line constructed in accordance with standard practices. Here ten wires are carried on a single crossarm, and when looking in the direction of the pole numbering of the line the wires are numbered beginning with the left-hand pin of the top crossarm. Assuming that the wire layout on this line is an ideal one, it will give us ten side circuits and five phantom circuits. Phantom groups will be made up of wires 1-4, 7-10, 11-14, 17-20 and 5-6 and 15-16. The last-mentioned phantom group made up of wires 5-6 and 15-16 is called a vertical phantom. Now if any of these circuits are loaded, the loading coils, mounted in proper loading coil cases, will be spaced 7.88 miles apart, this being the standard spacing for all open wire loading and corresponding to $\pi$ coils per wave-length at the circuit's "critical" or "cut-off" frequency.

The electrical properties of a circuit on such a line will depend, of course, upon the gauge of conductors, the type of circuit, i.e., whether loaded or non-loaded, side or phantom, and also upon whether the circuit takes a pole pair such as wires 5-6 or some other pair such as 1-2; if phantomed, whether the phantom be vertical such as phantom of wires 5-6, 15-16, or horizontal such as wires 1-4, etc. Though there may be several types of circuits represented on this one pole line, there are fixed constants for each type which do not change appreciably. The resistance, for example, is fixed by the gauge of wire. The capacity per mile is fixed by the gauge and the spacing between wires. All spacing with the exception of the pole pairs is twelve inches; the pole pair itself is eighteen inches. Table XV gives the actual physical makeup of standard open wire circuits and shows the various electrical constants, which may be calculated from the attenuation formula, etc.

While the makeup of long toll cables is not so well standardized as the layout of the open wire line, every physical cable circuit is made up of a twisted pair and every phantom is made up of a "quad" which consists of two side circuits in turn twisted together. The copper conductors are insulated by spiral wrappings of special insulating paper. Table XVI is similar to table XV and shows constants for the more common types of cable circuits.

These tables are given here for their reference value in long distance plant work and will not be discussed in detail. The constants shown in the various columns are those that we have discussed in previous Chapters. It might be stated, however, that these constants apply to more or less ideal conditions. To illustrate, the leakage, given in micromhos, will depend upon the atmospheric conditions and the condition of the line's insulation. Should the leakage become very high, the various constants such as attenuation, wave-length constant, the characteristic impedance, etc., would be appreciably changed. Furthermore, the effect of the low insulation may be quite different for a loaded circuit than for a non-loaded circuit. As an illustration it can be proven by the attenuation constant formula that when the insulation upon a loaded circuit becomes very low the effect of the loading is detrimental rather than helpful. (See Figure 270).

In both Tables XV and XVI it should be remembered that the constants are calculated for a single frequency which is 796 cycles, or $2\pi$ f cycles $=$ 5000. The tables do not give us any information as to variation of the constants for the range of telephonic frequencies. Most of these circuits, however, have their own inherent distortion or impairment of quality because the attenuation at other frequencies within the voice range is not the same as that at the single frequency value where $2\pi$ f $=$ 5000. To illustrate, in the case of a #19 gauge cable circuit, we have considerable distortion of the voice current due to this effect before the cable is loaded, and a very good circuit in this respect after the circuit is loaded with low inductance value loading coils spaced 6,000 feet apart. Figure 275 shows a number of curves illustrating the degree to which this variation of attenuation may be expected in typical circuits. The degree to which quality in a telephone conversation is impaired is reflected in these curves and we have no generally adopted standard for measuring distortion other than a comparison of the attenuation or loss in TU at different frequencies within the voice range. The 4-B and 6-A transmission measuring sets discussed in the preceding Article may be used for making such attenuation-frequency curves.

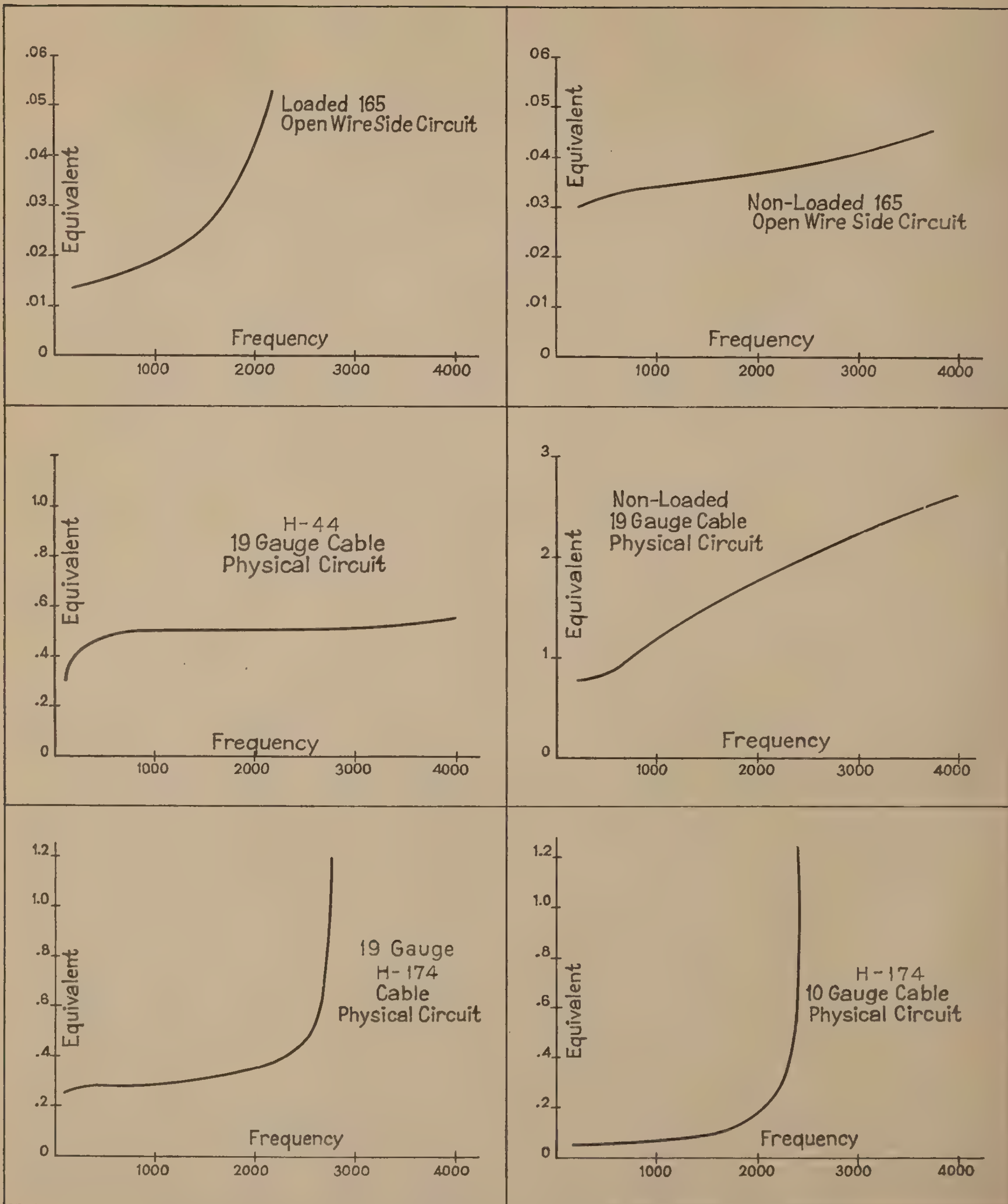



*Fig. 275—Attenuation—Frequency Curves for Standard Telephone Circuits.*

TABLE XV

## CHARACTERISTICS OF STANDARD TYPES OF OPEN WIRE TELEPHONE CIRCUITS AT 796 CYCLES PER SECOND

| | | | | | | Load Coil Constants Per Load Section | | Constants Assumed to be Distributed Per Loop Mi. | | | | Propagation Constant | | | | Line Impedance | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Polar | | Rectangular | | Polar | | Rectangular | | | | | | | |
| Type of Circuit | Gauge of Wires | Type of Loading | Code No. of Loading Coils | Spacing of Load Coils Miles | Position in Loading Section | R Ohms | L Henrys | R Ohms | L Henrys | C M.F. | G M.MHO | Magnitude | Angle Degrees + | $\alpha$ | $\beta$ | Magnitude | Degrees Angle — | R Ohms | X Ohms — | Wave Length Miles | Coils Per Wave Length | Velocity Loads Per Second W | Velocity Miles Per Second W | Cut-Off Frequency (Approx.) | Standard Transmission Equivalent TU Per Mile (1000 Cycles) |
| Pole Pair | Inches Diameter 0.104 | N. L. | — | — | — | — | — | 10.40 | 0.00394 | 0.00778 | 0.8 | 0.0294 | 75.47 | 0.00739 | 0.02845 | 756 | 13.35 | 736 | 175 | 224 | — | — | 178,300 | — | 0.075 |
| Physical | " | " | — | — | — | — | — | 10.40 | 0.00367 | 0.00835 | " | 0.02968 | 74.68 | 0.00784 | 0.02863 | 710.6 | 14.23 | 688.8 | 174.7 | 219.5 | — | — | 174,722 | — | 0.075 |
| " | " | W-240-S | 550 | 7.88 | — | 7.3 | 0.246 | 11.32 | 0.03487 | " | " | 0.08488 | 87.57 | 0.003604 | 0.08480 | 2033 | 1.33 | 2032 | 47.3 | 74.09 | 9.4 | 7485 | 58,976 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 10.40 | 0.00367 | " | " | 0.08678 | 87.22 | 0.004214 | 0.08668 | 1936 | 1.17 | 1935 | 39.42 | 72.49 | 9.19 | 7335 | 57,702 | 2440 | 0.032 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 2155 | 1.8 | 2153 | 67.67 | " | " | " | " | " | " |
| Side | " | N. L. | — | — | — | — | — | 10.40 | 0.00367 | " | " | 0.02968 | 74.68 | 0.00784 | 0.02863 | 710.6 | 14.23 | 688.8 | 174.7 | 219.5 | — | — | 174,722 | — | 0.075 |
| " | " | W-240-S | 550 | 7.88 | — | 9.66 | 0.246 | 11.63 | 0.03487 | " | " | 0.08545 | 87.55 | 0.00365 | 0.08544 | 2046 | 1.37 | 2045 | 48.75 | 73.5 | 9.33 | 7430 | 58,500 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 10.40 | 0.00367 | " | " | 0.09641 | 87.38 | 0.0044 | 0.09631 | 2122 | 1.02 | 2122 | 37.64 | 65.25 | 8.28 | 6580 | 52,000 | 2440 | 0.033 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 2416 | 1.66 | 2415 | 70.26 | " | " | " | " | " | " |
| Phantom | " | N. L. | — | — | — | — | — | 5.20 | 0.00223 | 0.01406 | 1.0 | 0.02941 | 77.1 | 0.006566 | 0.02867 | 418.3 | 12.10 | 409.0 | 87.68 | 219.1 | — | — | 174,404 | -- | 0.064 |
| " | " | W-150-P | 549 & 550 | 7.88 | — | 5.42 | 0.150 | 5.90 | 0.02128 | " | " | 0.08596 | 88.0 | 0.00300 | 0.08591 | 1223 | 1.20 | 1223 | 25.61 | 73.13 | 9.28 | 7375 | 58,211 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 5.20 | 0.00223 | " | " | 0.08788 | 87.81 | 0.003348 | 0.08782 | 1163 | 1.1 | 1163 | 21.66 | 71.54 | 9.08 | 7225 | 56,946 | 2420 | 0.027 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 1296 | 1.45 | 1296 | 32.80 | " | " | " | " | " | " |
| Pole Pair | 0.165 | N. L. | — | — | — | — | — | 4.14 | 0.00364 | 0.00845 | 0.8 | 0.02808 | 83.06 | 0.00339 | 0.02788 | 665 | 5.86 | 661 | 67.5 | 225 | — | — | 179,300 | — | 0.033 |
| Physical | " | " | — | — | — | — | — | 4.14 | 0.00337 | 0.00914 | 0.8 | 0.02816 | 82.6 | 0.003627 | 0.02793 | 616.1 | 6.40 | 612.3 | 68.68 | 225 | — | — | 179,100 | — | " |
| " | " | W-240-S | 550 | 7.88 | — | 7.3 | 0.246 | 5.06 | 0.03457 | " | " | 0.08833 | 88.65 | 0.002081 | 0.08831 | 1932 | 0.35 | 1932 | 11.80 | 71.15 | 9.02 | 7185 | 56,635 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 4.14 | 0.00337 | " | " | 0.09053 | 88.1 | 0.003107 | 0.09048 | 1831 | 0.23 | 1831 | 7.453 | 69.44 | 8.82 | 7010 | 55,274 | 2340 | 0.018 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 2061 | 1.1 | 2061 | 39.57 | " | " | " | " | " | " |
| Side | " | N. L. | — | — | — | — | — | 4.14 | 0.00337 | " | " | 0.02816 | 82.6 | 0.003672 | 0.02793 | 616.1 | 6.4 | 612.3 | 68.68 | 225 | — | — | 179,100 | — | 0.033 |
| " | " | W-240-S | 550 | 7.88 | — | 9.66 | 0.246 | 5.37 | 0.03457 | " | " | 0.08893 | 88.61 | 0.002145 | 0.08892 | 1945 | 0.40 | 1945 | 13.6 | 70.65 | 8.97 | 7140 | 56,350 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 4.14 | 0.00337 | " | " | 0.09054 | 87.87 | 0.00337 | 0.09048 | 2027 | 0.22 | 2027 | 7.66 | 69.5 | 8.82 | 7020 | 55,300 | 2340 | 0.018 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 2060 | 1.28 | 2059 | 46.14 | " | " | " | " | " | " |
| Phantom | " | N. L. | — | — | — | — | — | 2.07 | 0.00208 | 0.01509 | 1.0 | 0.02828 | 84.0 | 0.002956 | 0.02813 | 374.8 | 5.25 | 373.2 | 34.29 | 223.4 | — | — | 177,826 | — | 0.028 |
| " | " | W-150-P | 549 & 550 | 7.88 | — | 5.42 | 0.150 | 2.76 | 0.02113 | " | " | 0.08867 | 88.87 | 0.001754 | 0.08865 | 1175.0 | 0.38 | 1175 | 7.861 | 70.87 | 8.858 | 7052 | 56,413 | — | — |
| " | " | " | " | " | Mid-Coil | " | " | 2.07 | 0.00208 | " | " | 0.09090 | 88.4 | 0.002538 | 0.09086 | 1113 | 0.28 | 1113 | 5.509 | 69.15 | 8.644 | 6880 | 55,043 | 2360 | 0.015 |
| " | " | " | " | " | Mid-Section | " | " | " | " | " | " | " | " | " | " | 1255 | 0.95 | 1255 | 20.80 | " | " | " | " | " | " |

**NOTE 1.** A dash in the column, "Position in Loading Section", indicates that the corresponding values were computed on the assumption that the electrical constants were uniformly distributed along the line.

**NOTE 2.** Where Mid-Coil or Mid-Section appears in column, "Position in Loading Section", exact methods were used in determining the line characteristics: loading coil constants were not assumed distributed.

# TABLE XVI

## CHARACTERISTICS OF STANDARD TYPES OF PAPER CABLE TELEPHONE CIRCUITS AT 796 CYCLES PER SECOND

| Type of Circuit | Gauge of Wires | Type of Loading | Code No. of Loading Coils | Spacing of Load Coils Miles | Position in Loading Section | Load Coil Constants Per Load Section: R Ohms | Load Coil Constants Per Load Section: L Henrys | Constants Assumed to be Distributed Per Loop Mi.: R Ohms | Constants Assumed to be Distributed Per Loop Mi.: L Henrys | Constants Assumed to be Distributed Per Loop Mi.: C M.F. | Constants Assumed to be Distributed Per Loop Mi.: G M.MHO | Propagation Constant, Polar: Magnitude | Propagation Constant, Polar: Angle Degrees + | Propagation Constant, Rectangular: α | Propagation Constant, Rectangular: β | Line Impedance, Polar: Magnitude | Line Impedance, Polar: Angle Degrees — | Line Impedance, Rectangular: R Ohms | Line Impedance, Rectangular: X Ohms — | Wave Length Miles | Coils Per Wave Length | Velocity Loads Per Second W | Velocity Miles Per Second W | Cut-Off Frequency $f_c$ (Approx.) | Standard Transmission Equivalent TU Per Mile (1000 Cycles) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Physical | #22 A.W.G. | N. L. | — | — | — | — | — | 171 | 0.001 | 0.073 | 1.75 | .2499 | 45.70 | .1745 | .1789 | 684.5 | 44.03 | 492.1 | 475.80 | 35.12 | — | — | 27,956 | — | 1.7 |
| " | " | M-174-N | 583 & 584 | 1.66 | — | 10.6 | 0.175 | 177.39 | 0.1065 | " | " | .4527 | 80.65 | .0735 | .4462 | 1240.0 | 9.08 | 1224.0 | 195.80 | 14.07 | 8.57 | 6750 | 11,200 | 2160 | 0.8 |
| *Side | #19 A.W.G. | N. L. | — | — | — | — | — | 83.2 | 0.001 | 0.062 | 0.868 | .1627 | 46.60 | .1118 | .1182 | 524.7 | 43.23 | 382.3 | 359.40 | 53.16 | — | — | 42,315 | — | 1.09 |
| " | " | M-174-S | 583 & 584 | 1.66 | — | 14.26 | 0.175 | 93.79 | 0.1065 | " | " | .4094 | 84.92 | .0363 | .4078 | 1321.0 | 4.92 | 1316.0 | 113.20 | 15.41 | 9.3 | 7378 | 12,266 | 2350 | 0.33 |
| " | " | H-174-S | " | 1.135 | — | " | " | 97.75 | 0.155 | " | " | .4920 | 86.33 | .0315 | .4910 | 1588.0 | 3.52 | 1585.0 | 97.41 | 12.80 | 11.28 | 8965 | 10,189 | 2840 | 0.28 |
| " | " | H-245-S | 581 & 582 | 1.135 | — | 21.56 | 0.250 | 104.18 | 0.2213 | " | " | .5874 | 87.23 | .0284 | .5867 | 1895 | 2.60 | 1893.0 | 85.96 | 10.71 | 9.45 | 7510 | 8,525 | 2380 | 0.26 |
| " | " | H-44-S | 589 & 590 | 1.135 | — | 3.48 | 0.044 | 88.27 | 0.0397 | " | " | .2595 | 77.93 | .0543 | .2538 | 837.0 | 11.90 | 819.0 | 172.60 | 24.76 | 21.80 | 17370 | 19,709 | 5840 | 0.48 |
| *Physical | " | N. L. | — | — | — | — | — | 85.2 | 0.001 | 0.066 | 1.585 | .1678 | 46.55 | .1154 | .1218 | 508.5 | 43.18 | 370.8 | 348.00 | 51.58 | — | — | 41,058 | — | 1.09 |
| " | " | M-174-N | 583 & 584 | 1.66 | — | 10.6 | 0.175 | 91.59 | 0.1065 | " | " | .4222 | 84.98 | .0369 | .4206 | 1280.0 | 4.73 | 1276.0 | 105.60 | 14.94 | 9.00 | 7160 | 11,892 | 2280 | — |
| " | " | H-174-N | " | 1.135 | — | " | " | 94.54 | 0.155 | " | " | .5075 | 86.38 | .0320 | .5065 | 1540.0 | 3.48 | 1535.0 | 93.00 | 12.40 | 10.92 | 8695 | 9,870 | 2750 | — |
| " | " | H-245-N | 581 & 582 | 1.135 | — | 16.3 | 0.250 | 99.56 | 0.2213 | " | " | .6058 | 87.30 | .0285 | .6051 | 1836.0 | 2.43 | 1834.0 | 77.95 | 10.38 | 9.15 | 7275 | 8,262 | 2310 | — |
| " | " | H-44-N | 589 & 590 | 1.135 | — | 2.4 | 0.044 | 87.32 | 0.0397 | " | " | .2675 | 77.98 | .0557 | .2616 | 810.8 | 11.73 | 793.9 | 164.90 | 24.02 | 21.14 | 16860 | 19,120 | 5490 | — |
| *Side | #16 A.W.G. | N. L. | — | — | — | — | — | 42.2 | 0.001 | 0.062 | 0.868 | .1147 | 48.30 | .0763 | .0856 | 370.3 | 41.55 | 277.1 | 245.60 | 73.37 | — | — | 58,403 | — | 0.73 |
| " | " | M-174-S | 583 & 584 | 1.66 | — | 14.26 | 0.175 | 50.79 | 0.1065 | " | " | .4072 | 87.20 | .0199 | .4067 | 1314.0 | 2.65 | 1313.0 | 60.75 | 15.45 | 9.31 | 7410 | 12,298 | 2350 | 0.18 |
| " | " | H-174-S | " | 1.135 | — | " | " | 54.75 | 0.155 | " | " | .4907 | 87.90 | .0180 | .4904 | 1583.0 | 1.93 | 1582.0 | 53.41 | 12.81 | 11.29 | 8976 | 10,197 | 2840 | 0.16 |
| " | " | H-44-S | 589 & 590 | 1.135 | — | 3.48 | 0.044 | 45.27 | 0.0397 | " | " | .2512 | 83.50 | .0284 | .2496 | 810.5 | 6.35 | 805.5 | 89.64 | 25.17 | 22.18 | 17670 | 20,035 | 5840 | 0.25 |
| " | #13 A.W.G. | N. L. | — | — | — | — | — | 21.4 | 0.001 | " | " | .0826 | 51.50 | .0514 | .0646 | 266.3 | 38.35 | 208.8 | 165.20 | 97.26 | — | — | 77,419 | — | 0.49 |
| " | " | M-174-S | 583 & 584 | 1.66 | — | 14.26 | 0.175 | 29.99 | 0.1065 | " | " | .4066 | 88.32 | .0120 | .4064 | 1312.0 | 1.53 | 1312.0 | 35.11 | 15.46 | 9.31 | 7420 | 12,306 | 2390 | 0.109 |
| " | " | H-245-S | 581 & 582 | 1.135 | — | 21.56 | 0.250 | 40.38 | 0.2213 | " | " | .5864 | 88.88 | .0114 | .5863 | 1891.0 | 0.97 | 1891.0 | 31.80 | 10.72 | 9.45 | 7520 | 8,533 | 2380 | 0.107 |
| Phantom | #19 A.W.G. | N. L. | — | — | — | — | — | 42.6 | 0.0007 | 0.10 | 1.4 | .1460 | 47.35 | .099 | .1075 | 292.0 | 42.65 | 214.8 | 198.0 | 58.4 | — | — | 46,500 | — | 1.09 |
| " | " | M-106-P | 583 & 584 | 1.66 | — | 6.9 | 0.106 | 46.76 | 0.0647 | " | " | .404 | 85.90 | .0289 | .403 | 809.0 | 4.10 | 807.0 | 58.0 | 15.58 | 9.38 | 7475 | 12,400 | 2380 | 0.26 |
| " | " | H-106-P | " | 1.135 | — | " | " | 48.68 | 0.0942 | " | " | .486 | 87.05 | .025 | .486 | 973.1 | 2.90 | 972.0 | 49.2 | 12.92 | 11.38 | 9065 | 10,290 | 2880 | 0.22 |
| " | " | H-155-P | 581 & 582 | 1.135 | — | 10.3 | 0.155 | 51.68 | 0.1377 | " | " | .588 | 87.86 | .0210 | .588 | 1175.0 | 2.15 | 1174.0 | 44.1 | 10.68 | 9.41 | 7495 | 8,500 | 2340 | 0.21 |
| " | " | H-25-P | 589 & 590 | 1.135 | — | 1.71 | 0.025 | 44.11 | 0.0227 | " | " | .247 | 79.40 | .0453 | .242 | 495.0 | 10.60 | 485.0 | 91.0 | 25.97 | 22.90 | 18180 | 20,620 | 5900 | 0.40 |
| " | #16 A.W.G. | N. L. | — | — | — | — | — | 21.1 | 0.0007 | " | " | .103 | 49.71 | .067 | .077 | 207.0 | 40.29 | 158.0 | 133.5 | 81.60 | — | — | 65,000 | — | 0.64 |
| " | " | M-106-P | 583 & 584 | 1.66 | — | 6.9 | 0.106 | 25.26 | 0.0647 | " | " | .403 | 87.76 | .0158 | .403 | 805.6 | 2.18 | 805.0 | 30.7 | 15.59 | 9.39 | 7480 | 12,410 | 2380 | 0.15 |
| " | " | H-106-P | " | 1.135 | — | " | " | 27.18 | 0.0942 | " | " | .486 | 88.35 | .014 | .485 | 971.0 | 1.65 | 970.0 | 28.0 | 12.95 | 11.40 | 9090 | 10,310 | 2880 | 0.13 |
| " | " | H-25-P | 589 & 590 | 1.135 | — | 1.71 | 0.025 | 22.61 | 0.0227 | " | " | .241 | 84.33 | .02382 | .2393 | 481.0 | 5.65 | 478.0 | 47.3 | 26.25 | 23.13 | 17710 | 20,100 | 5900 | 0.21 |
| " | #13 A.W.G. | N. L. | — | — | — | — | — | 10.70 | 0.0007 | " | " | .075 | 54.02 | .0441 | .0607 | 150.0 | 35.95 | 121.0 | 88.0 | 103.50 | — | — | 82,390 | — | 0.42 |
| " | " | M-106-P | 583 & 584 | 1.66 | — | 6.9 | 0.106 | 14.86 | 0.0647 | " | " | .403 | 88.50 | .0105 | .4020 | 804.0 | 1.5 | 803.5 | 21.0 | 15.63 | 9.42 | 7500 | 12,447 | 2380 | 0.089 |
| " | " | H-155-P | 581 & 582 | 1.135 | — | 10.3 | 0.155 | 19.78 | 0.1377 | " | " | .587 | 89.13 | .0089 | .5868 | 1174.0 | 0.78 | 1174.0 | 16.1 | 10.70 | 9.43 | 7500 | 8,510 | 2340 | 0.085 |

**NOTE:** A dash in the column, "Position in Loading Section", indicates that the corresponding values were computed on the assumption that the electrical constants were uniformly distributed along the line.
* = All physicals assumed to be in non-quadded cable, and all sides and phantoms in quadded cable.

## CHAPTER XXIII

## USE OF TELEPHONE REPEATERS

### 134. Limitations of Toll Circuits Without the Use of Repeaters

In Tables XV and XVI we have columns showing the transmission equivalent per mile of each kind of line circuit in TU. For example, the equivalent of a #19 gauge non-loaded cable is greater than unity,—meaning that one mile of this class of circuit will attenuate the voice current more than one TU. Contrasted with this we have the equivalent of a loaded 165 open wire side circuit given as .018,—meaning that the attenuation per mile is this fraction of a TU, or that it would require 55.5 miles of such a circuit to attenuate the voice current as much as one TU.

In long distance telephone practice we employ that grade of circuit in each particular case which is required to render satisfactory telephone service. It would not be economical to construct all circuits of 165 copper wire and load each circuit, thereby providing the most efficient open wire circuits; and even with the most efficient circuits and the standardized practices of loading there are limitations to the distance over which a satisfactory telephone conversation can be given. It is a known fact that if the overall equivalent of a given circuit in TU when added to the equivalent of the terminating apparatus and subscribers' loops becomes appreciably greater than 30 TU, the volume of energy from the speaker to the listener is attenuated to such an extent as to render the conversation faint. A poorer grade of transmission would result in either a complaint from the subscriber or an inclination on the subscriber's part to refrain from the use of such service at times when he otherwise might employ it. There is a commercial limit, therefore, to the use of even the highest grade line facilities and loading practices in long distance telephone transmission. Consequently, to give service over extremely long distances **we now depend upon means of amplifying the energy at various points along the line, for which we use the telephone repeater. Moreover, there are economic considerations favoring the use of telephone repeaters in connection with lower grade facilities to supplant the practice of loading or the use of high grade facilities,** as well as to extend the range of commercial transmission.

As an illustration of extending the range of transmission, the "22-type" repeater can be used in connection with open wire lines having uniform impedance characteristics to give a transmission "gain", depending upon conditions but not exceeding about eighteen TU at each repeater point. The use of such repeaters with an average spacing of 500 to 600 miles in connection with high grade loaded 165 circuits having very smooth impedance characteristics made the first transcontinental telephone service possible. This same service was later improved by removing the loading coils and employing additional repeaters, so that the spacing between repeater stations was reduced to about 250 miles. This was a case where the use of telephone repeaters supplanted the practice of loading not primarily because of economic reasons, but to give better transmission.

The telephone repeater is, in certain respects, a very flexible piece of apparatus. It may be used as a part of the cord circuit at a switching point between various long distance circuits to supply the required transmission gain for switched connections when such gain is not required for terminating connections, or it may be used as a fixed part of the makeup of a particular circuit, and located at the terminals or at points along the route of the circuit, in which case it is called a "through line repeater". In one sense, however, the repeater is not a self-contained unit. It cannot be used at random on any telephone circuit. Rigid "balance" and other requirements introduce certain complications and influence a number of other plant practices; for instance, irregularities in loading that would not appreciably impair transmission on a nonrepeatered circuit may seriously interfere with the use of telephone repeaters. Yet the effectiveness of repeaters in increasing the range of transmission or permitting the use of lower grade facilities has justified some extraordinary changes in plant construction and maintenance standards.

In preceding Chapters we studied the principles of operation of the telephone repeater. We first learned that a bridge type of transformer would permit the use of one-way amplifying devices on two-wire circuits for two-way transmission. We then studied the operation of the vacuum tube as a suitable device for use in amplifying circuits. It will be recalled that three types of telephone repeaters are employed in connection with long distance transmission, viz; the 22-type, the 44-type, and the 21-type. In this Chapter we shall discuss more in particular the field of use of the various types of repeaters, the gains that may be secured under actual operating conditions, the balance requirements for obtaining these gains, and economic factors that must be considered throughout.

### 135. Economic Considerations

In determining the field of use of telephone repeaters in the plant there are in the very beginning economic questions to be given consideration such as—

1. Use of repeaters versus loading.
2. Cord circuit sets versus through line sets.
3. Repeatered cable circuits versus open wire circuits.

4. 21-type repeaters versus 22-type (in cases where the use of 21-type is possible).

5. 4-wire small gauge cable repeatered circuits versus two-wire larger gauge cable repeatered circuits.

While these are primarily problems for the telephone engineer, they are of general and fundamental interest.

In the case of "repeaters versus loading" it is unquestionably more economical to provide a cord circuit set at some intermediate switching point than to load a large number of terminating circuits when satisfactory transmission can be given over the terminating circuits on all but the occasional switched connection. On the other hand a more careful study would have to be made to determine the use of one or more through line repeaters on a single circuit in preference to loading. Local conditions might be such that there were no intermediate offices suitable for repeater installations in which case loading would be the more economical solution, otherwise the use of repeaters might be the more economical.

The above case, of course, applies only to open wire, as cable circuits when used for long toll service are both loaded and repeatered. But there are other problms in connection with the cable application which are even more complex. In the first place a group of circuits of a given grade, serving a thickly populated section of the country, may be more economical on a cable and repeater basis, whereas a single circuit in a thinly populated territory may be more economical on an open wire basis. Then if it is decided to employ cable there is the question of the particular class of facility and type of repeater. If the circuit is comparatively short and handles terminating business only it may be possible to use, at its mid-point, a 21-type repeater which is much cheaper than the 22-type but does not operate satisfactorily in tandem with other repeaters. If the circuit is a long one there remains to determine whether a single cable pair will be used in connection with 22-type repeaters or two cable pairs, perhaps of smaller gauge, in connection with the four-wire 44-type repeaters. In all these determinations there are to be considered such factors as local conditions, class of facility desired, number of facilities desired, flexibility, and effect upon future plans, which tend to complicate the problem and must not be overlooked by the engineer.

### 136. Repeater Gains

The permissible transmission gains will depend in most cases upon the conditions under which repeaters are operated. The amount of gain which the amplifying unit itself will give is usually in excess of that desired or that which plant conditions will permit. Yet it should not be forgotten that there is a limit to the amount of energy that any particular amplifying circuit can handle, and even before reaching the limit distortion makes its appearance. In the case of 44-type repeaters having two stages of amplification it is important that the gain be so adjusted between the first and second stages as to not overload the first stage; when so adjusted the two stages will give a combined gain of 50 TU or more without appreciable distortion. In this set the **working limits,** though very high, are established by crosstalk considerations rather than "balance".

In adjusting the gains of through line 22-type repeater sets, the ordinary limits for open wire use are as follows: **With the volume of transmission leaving a subscriber's line having a short loop defined as zero transmission "level", a "22-type" repeater having a B-battery of constant voltage may be operated to deliver a volume of transmission not exceeding the zero level by more than six TU for 22-A-1 repeaters or 10 TU for 22-B-1 types, but no open wire repeater regardless of spacing should be expected to give more than an eighteen TU gain.** However, these limiting factors apply only to the ideal conditions. If for instance there is a fluctuating B-battery voltage, as is the case with the ordinary telegraph battery, the zero level must not be exceeded by more than one TU.

In 4-wire cable circuits employing 44-type repeaters where crosstalk rather than balance limits the gain at any one station, much higher gains are permissible. Here it is permissible to operate the 44-type sets between an input volume not weaker than about 25 TU below zero level and a delivered output not greater than about 10 TU above the zero level. This means a possible gain of thirty-five TU and under this condition the energy delivered is nearly 2000 times as great as the energy received. This extreme energy ratio is the reason for the crosstalk limitation. If we imagine a case where an incoming cable pair is adjacent to an outgoing cable pair of any other four-wire cable circuit and there exists a small crosstalk unbalance from one pair to the other, the highly energized circuit may transfer a quantity of energy which although a very small and almost negligible fraction of its own energy is nevertheless quite appreciable compared to the energy in the other circuit which is only 1/2000th as great in value. This crosstalk energy returns to the repeater station with the incoming transmission and is amplified along with, and to the same degree as, the incoming transmission, thereby becoming audible and causing objectionable crosstalk. There are various layouts for minimizing this crosstalk such as using separate cables for transmission in the two directions or segregating the pairs of a single cable into selected groups.

Returning to the more general subject of repeater gains, the adjustments that are required for a number of tandem repeaters can be illustrated best by an "energy level diagram". Figure 276 gives such a diagram for a transcontinental circuit transmitting west to east. In the diagram the vertical ordinates represent TU transmission with losses charted downward and gains charted upward.

The gains of the various telephone repeaters are naturally straight vertical lines while attenuation losses between repeater stations are lines sloping downward. If we follow this zigzag curve to the New York end we see a net equivalent for the circuit of 14 TU. This is an application of through line 22-type repeaters where terminal repeaters are used and where some of the repeaters are of the 22-B-1 or "high energy level" type. Another illustration of the transmission level diagram is shown by Figure *277* which is for a four-wire circuit equipped with 44-type repeaters.

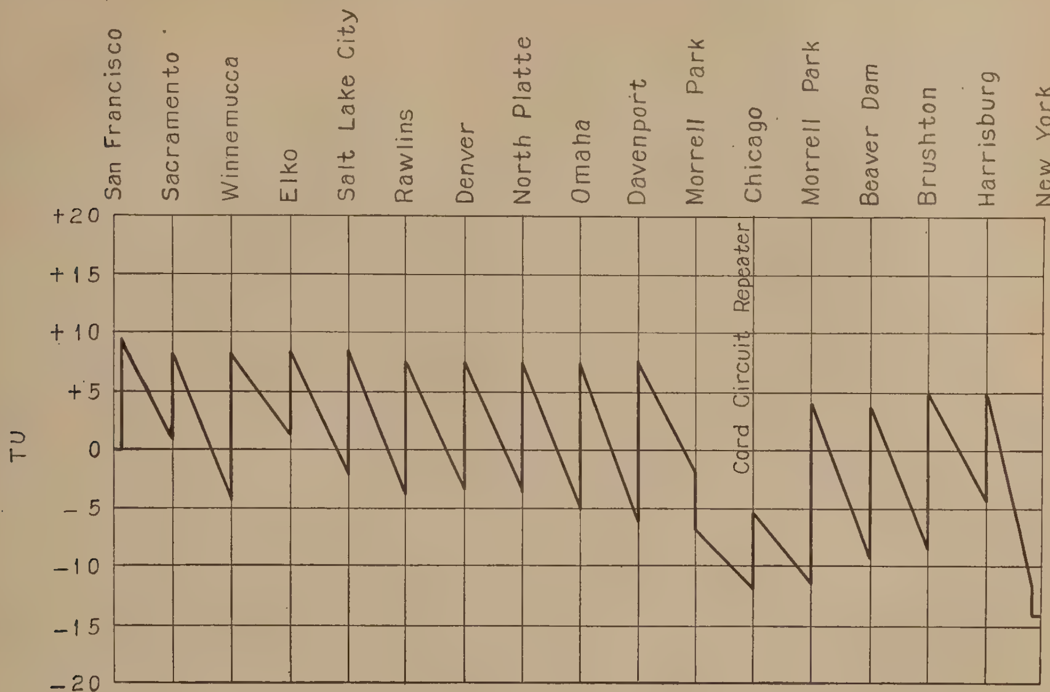



*Fig. 276—Transmission Level Diagram for Transcontinental Connection West to East.*

## TABLE XVII

## TRANSMISSION EQUIVALENTS OF 16 AWG AND 19 AWG CABLE PER MILE OF CIRCUIT AT 55° F. SHOWING YEARLY VARIATIONS IN EQUIVALENTS ON ACCOUNT OF TEMPERATURE CHANGES

| | | 16 AWG | | | | 19 AWG | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Side | | Phantom | | Side | | Phantom | |
| Loading | Type | At 55° F | Yearly Variation | At 55° F | Yearly Variation | At 55° F | Yearly Variation | At 55° F | Yearly Variation |
| H-245-106 | AE. | .16 | ± .016 | .13 | ± .013 | .26 | ± .028 | .22 | ± .025 |
| | U.G. | | ± .005 | | ± .004 | | ± .009 | | ± .008 |
| H-174-63 | AE. | .16 | ± .017 | .16 | ± .018 | .28 | ± .031 | .28 | ± .032 |
| | U.G. | | ± .006 | | ± .006 | | ± .010 | | ± .011 |
| H-44-25 | AE. | .25 | ± .029 | .21 | ± .024 | .48 | ± .055 | .40 | ± .047 |
| | U.G. | | ± .010 | | ± .008 | | ± .018 | | ± .016 |

One of the most important points in telephone repeater maintenance is to keep repeater gains so adjusted as to prevent wide variation in a circuit's equivalent due to conditions either affecting the attenuation of the line or the calibration of the repeaters. Perhaps the most extreme illustration of this is the case of temperature changes causing variation in the attenuation of cable conductors. This variation is illustrated by Table XVII which gives the variation of equivalent due to seasonal changes in temperature, using a maximum variation in air temperature of 100 degrees F. A cable circuit several hundred miles in length will give a variation even in excess of the circuit's net equivalent (gross equivalent less repeater gains) unless repeater gains are regulated to adjust for temperature conditions. There is in use a regulating device which automatically varies the gains of certain of the repeaters on long and important circuits to compensate for changes of the equivalents of the cable sections due to temperature variations. Its principle of operation employs a spare pair in the cable connected as the arm of a Wheatstone bridge circuit having a voltmeter relay to control the potentiometer settings at the regulating repeater.

Another variation in overall transmission may be introduced by the variation of the repeater gains which depend upon such factors as A and B battery voltage variation, length of service of tubes, etc. This is a matter of careful repeater maintenance and frequent transmission tests over repeatered circuits.

### 137. Network Balance

In two-wire circuit practice, gains are usually limited by the degree of balance which it is possible to secure between each telephone line and its balancing network which is associated with the bridge transformer. In other words, the allowable working gain of a 22-type telephone repeater will depend upon the gain that makes the repeater "sing" or rather appreciably impairs the quality, due to the unbalance between the lines and the associated networks. Just before the "singing" point is reached this impairment of quality is quite noticeable. Here then **we are concerned as much with the characteristic impedance of the line as with the attenuation constant.** The extent to which the repeater may improve transmission will depend directly upon the

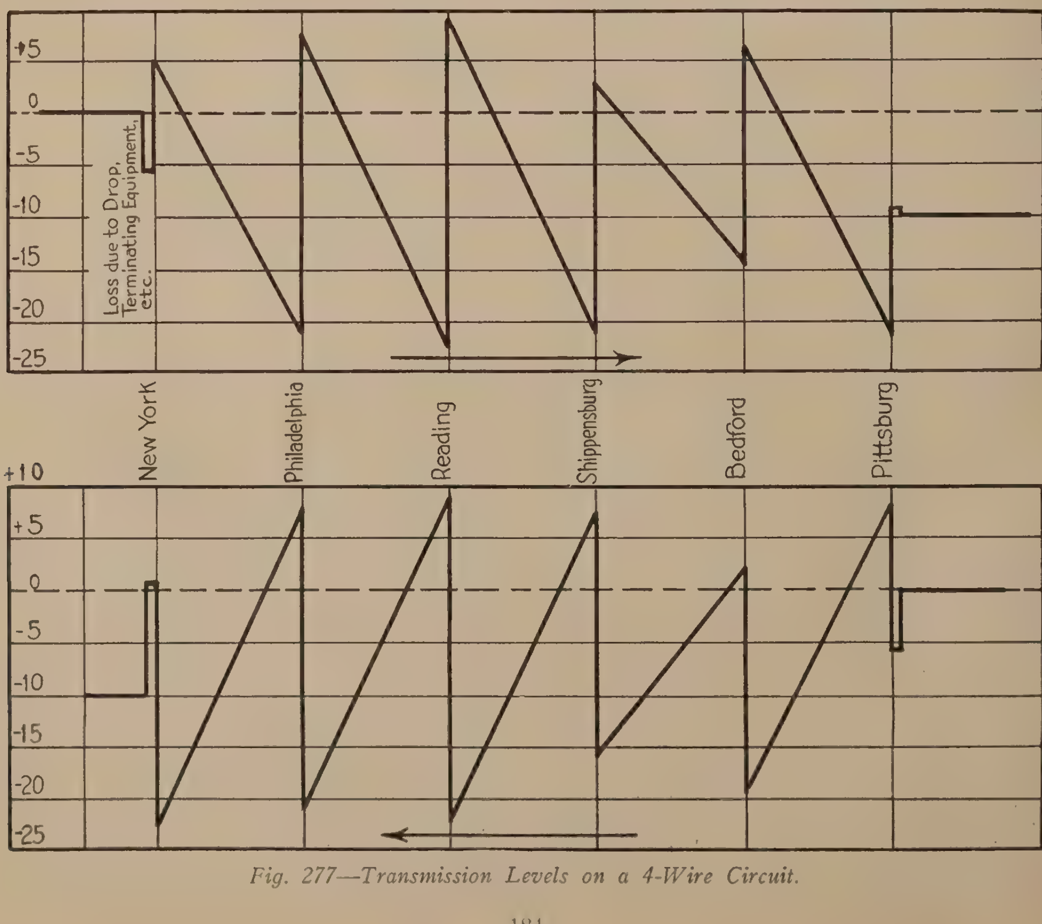



*Fig. 277—Transmission Levels on a 4-Wire Circuit.*

degree to which the network balances the telephone line. In turn the degree of balance will depend first upon the "smoothness" of the telephone line's impedance throughout the range of voice current frequency, and second, upon the adjustment that it is practicable to make for the effect that terminating conditions have upon this impedance.

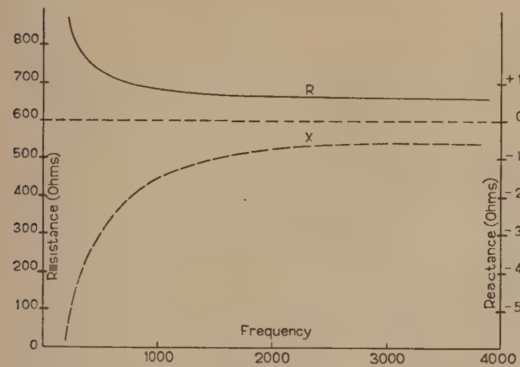



*Fig. 278—$Z_o$ for Non-Loaded 104 O.W. Physical Circuit.*

The basic requirements as to balance are perhaps best illustrated by Figure 278. Here we have the R and X components of the characteristic impedance $Z_o$ for non-loaded 104 open wire plotted with respect to the voice frequency band. It will be seen that the resistance component of the characteristic impedance becomes appreciably lower at the high frequencies and there is likewise a marked change in the value of the negative reactance.

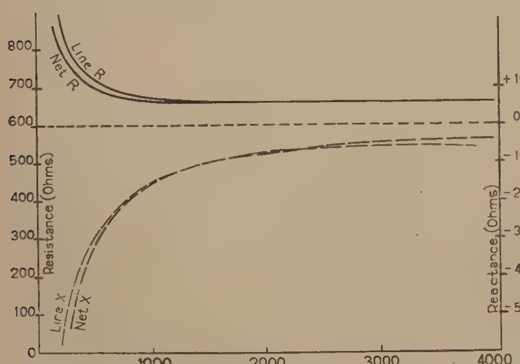



*Fig. 279—Impedance Characteristics of Non-Loaded Circuit and Corresponding Network.*

Now, to balance such a circuit a network must be designed with impedance components that not only equal those of the line at some one frequency, but vary similarly with the impedance of the line at all frequencies within the voice current band. Figure 279 compares the characteristic line impedance shown by Figure 278 with the impedance of the standard network used to balance this type of line.

The design of the basic network for a non-loaded open wire circuit is illustrated by Figure 281-A. This simple arrangement with proper values of resistance and capacity will very closely approximate the impedance components of the line itself. It will not, however, take care of the terminating conditions such as toll entrance cable, etc. Furthermore, it balances only the characteristic impedance of the circuit, i.e., the circuit must be in effect infinite in length or in other words terminated at the distant end in an impedance equal to the characteristic impedance. Consequently, telephone repeater balance even in the non-loaded circuit case involves considerations other than the design of a mere basic network which has an impedance approximating that of the characteristic impedance of the line. These balance requirements, however, are general and will be discussed after considering the basic network for the loaded type of circuit.

In open wire work it is usually more difficult to secure a high degree of network vs. line balance for loaded circuits than for non-loaded circuits. Furthermore, any slight irregularity in the loading, such as improper inductance values of the coil or inaccuracy in loading coil spacing, causes greater variations in the characteristic impedance of the line than in the attenuation, and loaded lines that may be satisfactory from a transmission standpoint are frequently not satisfactory for telephone repeater operation.

A basic network for a loaded circuit usually has a more complex design than a basic network for a non-loaded circuit. In this design some assumption must be made regarding the loaded circuit's termination, i.e., the basic network must be chosen to balance a loaded circuit terminating at a mid-coil* point, a mid-section point, or some fraction of the section other than mid-section. For example, Figure 280-A shows the resistance component of the impedance of a theoretical loaded line having no resistance for various forms of termination, the frequency band being that up to and including the critical frequency. The scale for frequency is shown as fractions of the critical frequency rather than as cycles in order that the curves may apply to any theoretical loaded line. Figure 280-B shows the corresponding reactance components. Here we can clearly see that the sending end impedance of a loaded line is appreciably affected by the termination.

A little inspection of Figure 280 will show that for a .2 or .8 section termination a plain non-inductive resistance will approximate the resistance component of the circuit as this resistance component remains nearly constant through the band of frequencies that the loaded circuit would be required

*Mid-coil termination means that the end of the circuit is equipped with a loading coil of half the normal inductance value, and that the section from this half coil to the first line coil is built out to be equivalent in capacity to a full section.

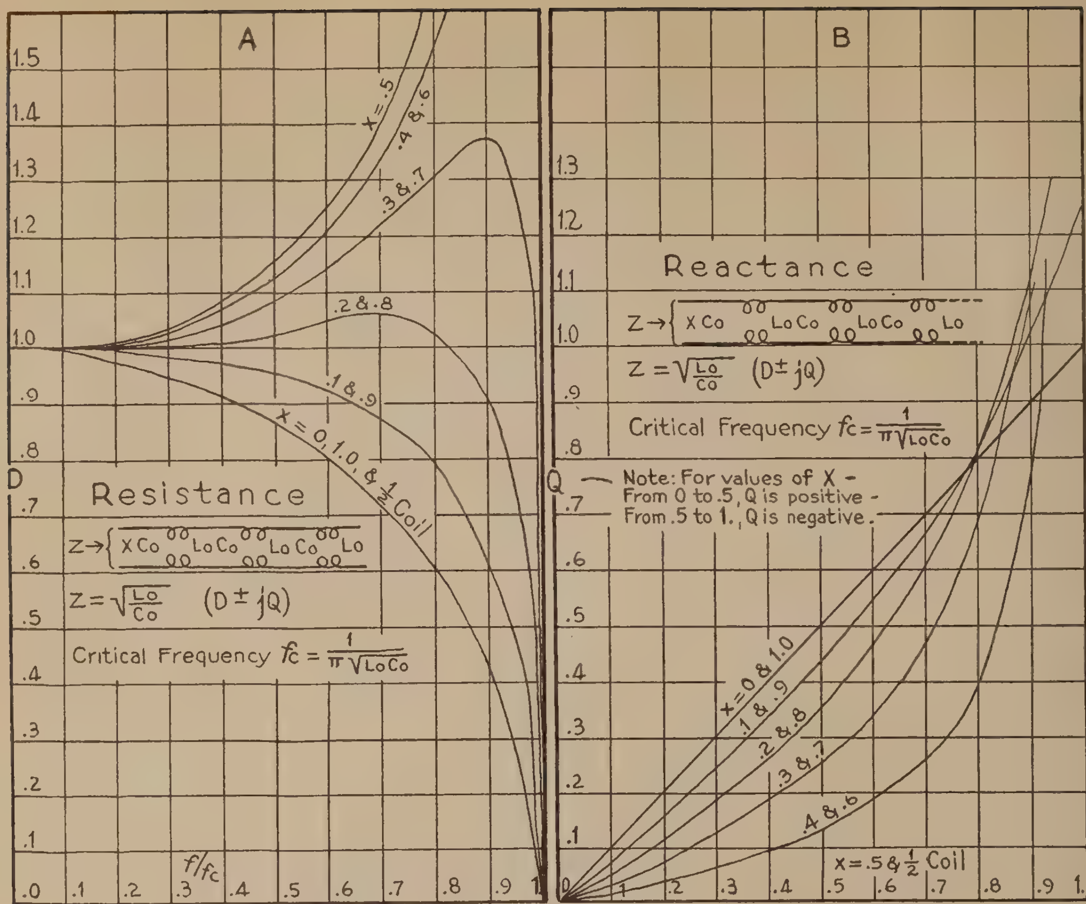



*Fig. 280—Characteristic Impedance Components of Theoretical Loaded Line.*
*(Line has no resistance or distributed Inductance)*

to transmit. This is true, however, only for these two terminating conditions. If we should choose, therefore, the .2 section sending end termination as that for which the basic balancing network would be designed, we would only need to connect in series with a resistance some combination of inductance and capacity that would approximate the corresponding reactance component shown in Figure 280-B in order to obtain a network which would simulate almost exactly the theoretical loaded line and, except at very low frequencies where the resistance of the actual line causes the impedance to depart appreciably from that of the theoretical line, would closely approximate an actual loaded line. This combination happens to be a capacity value in parallel with an inductance value; a schematic diagram for a basic network for a loaded open wire circuit of .2 termination is shown in Figure 281-B.

For balancing loaded cable circuits, however, more exact simulation at the low frequencies is usually required than can be obtained with this simple network and networks of somewhat more complex design are employed. Figure 281-C illustrates the design of the standard "precision" type of network used for balancing 16 and 19 gauge H-174-S and H-63-P cable circuits. These networks are designed to balance the line circuit at .181 section for the H-174-S circuits of both gauges and at .158 section for the H-63-P circuits. The design of the standard type of network used for balancing 19 gauge H-44-S and H-25-P cable circuits at .2 section is shown by Figure 281-D. The inductance, capacity and resistance values are of cource different for each different type of facility.

The networks are usually so encased as to be mounted on coil racks or relay racks and are similar in their outside mechanical appearance to repeating coils when so mounted. They are either designated with a red line or some other special marking that permits them to be easily identified as balancing networks and not mistaken for repeating coils.

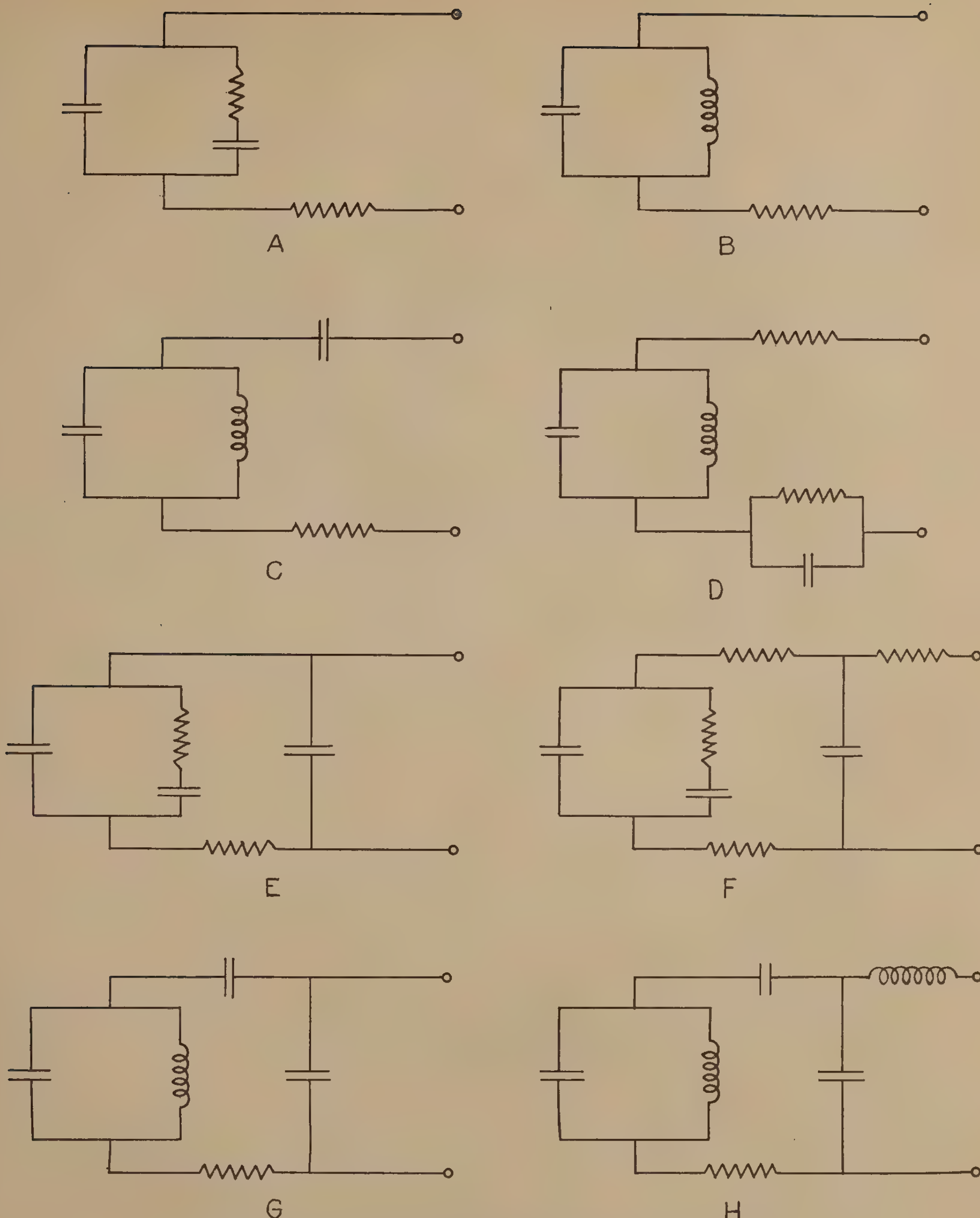



*Fig. 281—Circuits of Basic Networks and Building-Out Sections.*

### 138. The Line Termination

As stated in the foregoing, the basic network is only intended to balance the characteristic impedance of a smooth line of infinite length in the case of a non-loaded circuit, or the .2 section * termination sending end impedance for a smooth line of infinite length in the case of the loaded circuit, but the actual sending end impedance of the circuit may vary widely from the particular impedance which the basic network balances due to various reasons:

* .181 or .158 section in the four cases noted above.

a. At the repeater station in question the line may be brought in through toll entrance cable, etc.

b. In the case of the loaded circuit, the termination may not be at the .2 section point and as in **a** there may be toll entrance cable, etc.

c. The circuit may be equipped with terminating apparatus such as composite sets, repeating coils, composite ringers, etc.

d. The circuit may have irregularities due to intermediate submarine cables, etc.

e. The termination of the circuit at the distant end may introduce irregularites which do not permit the circuit to act as a circuit of infinite length.

It is the practice to make adjustments on the network side of the telephone repeater's bridge transformer to take care of **a** and **b** above by means of building-out condensers, i.e., if a non-loaded circuit has a short section of toll entrance cable there will be a capacity value equal to that of the capacity of the cable bridged directly across the network, as illustrated by Figure 281-E. If it has a long section of toll entrance cable it may be necessary to compensate for the resistance as well as the capacity, and accordingly, a bulding-out section with both a resistance and condenser, as shown in Figure 281-F may be used.

Similarly, in the case of the loaded circuit, if the capacity on the office side of the last loading point is greater than that corresponding to .2 loading section, it will be necessary to build out the basic network to adjust for this capacity as shown in Figure 281-G. If, on the other hand, the circuit should be so terminated that the capacity from the office side of the last loading coil was less than that of .2 loading section it would be necessary to install a bridged building-out condenser across the **line** of such value as to make the termination equivalent to .2 of a section.

In the foregoing cases we are assuming building-out conditions for the simplest termination. It is sometimes the practice in open wire work to effect a half loading coil termination, i.e., to install in the office a loading coil having an inductance value equivalent to half that of a line loading coil, and so build out the section on the line side of this coil as to simulate a full loading section between this coil and the first line coil. In this case the basic network, which balances only .2 of a section, would require a building-out condenser of value equal to .8 of a section and a half load coil balancing unit (retardation coil) connected as shown in Figure 281-H. The half loading coil termination in an office has certain advantages when making a switch without the use of a telephone repeater between two loaded lines. With such a termination the switched connection introduces the minimum irregularity in the loading, and if a telephone repeater is used at the distant end of either line the line as a whole will be equivalent to a smoothly loaded line of greater length. A half-section termination, however, is more generally used as it accomplishes this same result and is more satisfactory from a balance standpoint.

In determining the proper value of building-out condenser to be used, not only must we consider

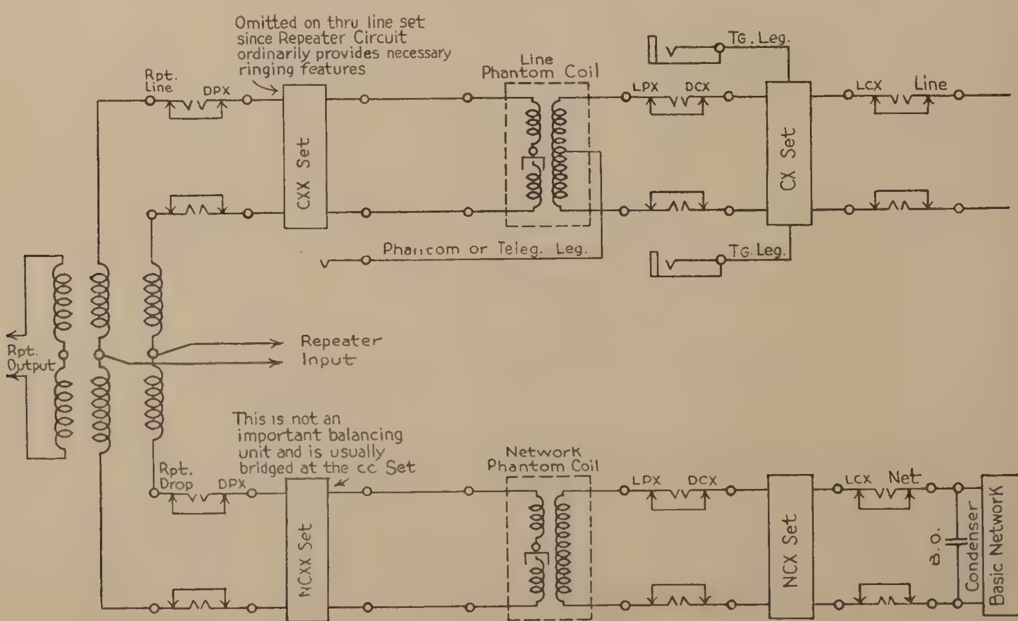



*Fig. 282—Line and Balancing Equipment.*

the toll entrance cable proper but all office cabling from the protectors to the first apparatus unit installed on the circuit, i.e., to the capacity of the toll entrance cable terminated at the frame would be added the capacity of the office cabling from the distributing frame to the testboard and from the testboard to some equipment unit such as a composite set.

Now in order to balance any apparatus that may be associated with the circuit such as composite sets, repeating coils, etc., it is necessary that either identical apparatus or a form of "dummy" apparatus having identical electrical characteristics in so far as impedance is concerned, be connected on the network side of the bridge transformer in the same order and with a cabling arrangement similar to that of the apparatus on the line side of the bridge transformer. That is to say, by having an equipment unit on the network side to balance a unit in the corresponding position on the line side we are effecting a more accurate bridge transformer balance; or we might say that looking toward the basic network as though it were a line we must have an electrical circuit identical to that on the actual line side of the bridge transformer. This is illustrated for a typical case in Figure 282 which gives a complete diagram of the network circuit and the line circuit.

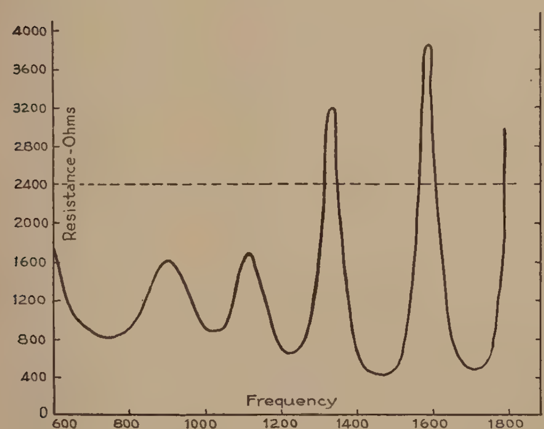



*Figure 283*

Referring now to d above, it is not usually feasible to make any network adjustments at the repeater station to compensate for irregularities in the line other than terminating ones. Such irregularities must be dealt with by actually clearing them if they are due to some line trouble, by the use of line building-out condensers as described in Article 130, or by working the telephone repeaters at correspondingly lower gains. The location and seriousness of line irregularities can be determined by a series of tests that will be described later. These irregularities manifest themselves as a series of "humps" in the impedance components of the line and the farther the irregularities are away from the station the less pronounced the "humps" become but the closer together they appear. The curve in Figure 283 illustrates the resistance component of the impedance of a circuit having an impedance irregularity.

The remaining reason given in the foregoing for the unbalance between network and line is that due to termination at the distant end of the circuit, or in other words that due to the condition where the line does not act as though it were infinite. In some cases this is a condition that must be tolerated with a resultant decrease in the permitted repeater gain. On the other hand, for very important service and particularly for service where several through line telephone repeaters are operated on a single circuit, it is possible to reduce the irregularity due to distant termination to a minimum by employing a repeater circuit that has a "passive impedance" closely approximating the characteristic impedance of the circuit. Here we mean by passive impedance **the impedance of the telephone repeater considered only as a complicated network of definite impedance value, terminating the circuit** (i.e., neglecting the amplified energy it supplies to the circuit *.)

If this definite impedance value be one giving ideal line termination it will present minimum irregularity to repeaters at adjacent stations.

### 139. Gain-Frequency Characteristiics

In Figure 275 are shown a number of curves illustrating the degree to which certain typical telephone circuits introduce a variation in the attenuation over the voice current band of frequencies.

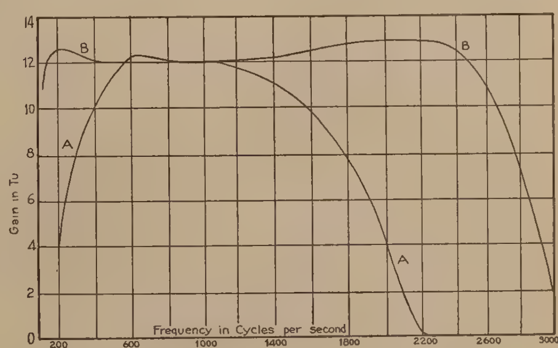



*Fig. 284—Gain-Frequency Characteristic of Repeaters.*

While this is an important consideration in analyzing the quality that might be expected over a given circuit, it is equally important to consider the "gain-frequency characteristics" of telephone repeaters

*The passive impedance of a repeater can be determined by setting the potentiometer of one side on step zero and making measurement from the other side.

that might be used at various points. Figure 284-A illustrates the gain-frequency curve for a type of through-line telephone repeater in general use on open wire circuits adjusted for an effective gain of 12 TU at 1000 cycles. Here we find that the repeater gives a nearly constant gain for frequencies between 1400 and 2200 cycles, and a suddenly decreasing gain for frequencies below 600 cycles. Contrasted with this is a repeater of more recent design which extends the band of frequencies having more or less constant amplification from less than 200 cycles to 2400 cycles, and extending with some degree of amplification beyond the latter frequency. The latter type of repeater giving constant amplification over a wide band naturally causes almost negligible distortion, and repeaters of the former type cause but little serious distortion when used on relatively short circuits for ordinary service. In the improved type, however, the balance requirements are more rigid in that the network must balance the line over a widely extended range of frequencies. In the case of loaded circuits or circuits not having absolutely smooth characteristics this balance requirement is a difficult one to meet and maintain since as will be seen from Figures 278 and 279 the basic network does not conform exactly to the line characteristics at the higher and lower limits of the voice frequency band.

In connection with the use of telephone repeaters quality considerations, therefore, involve more than the combination of gain-frequency curves and loss-frequency curves. Any inherent unbalance in the bridge transformer will permit the voice current energy to circulate to a degree through the repeater amplifiers and this energy superposed on the direct transmission is very detrimental to quality. Referring again to Figure 284 we could effect an improvement of quality by employing the repeater B only by meeting rather exacting balance requirements; for use under less satisfactory balance conditions repeater A would perhaps give the better quality.

The standards for telephone repeater balance have introduced one of the most important maintenance considerations in the telephone plant. Periodic tests are prescribed for checking the degree of balance which obtains on every repeatered circuit regardless of whether equipped with a through line repeater set or equipped at its terminating end for cord circuit repeater use. The simplest of these tests and the one made with the greatest frequency is the "21" circuit test which by converting the re-

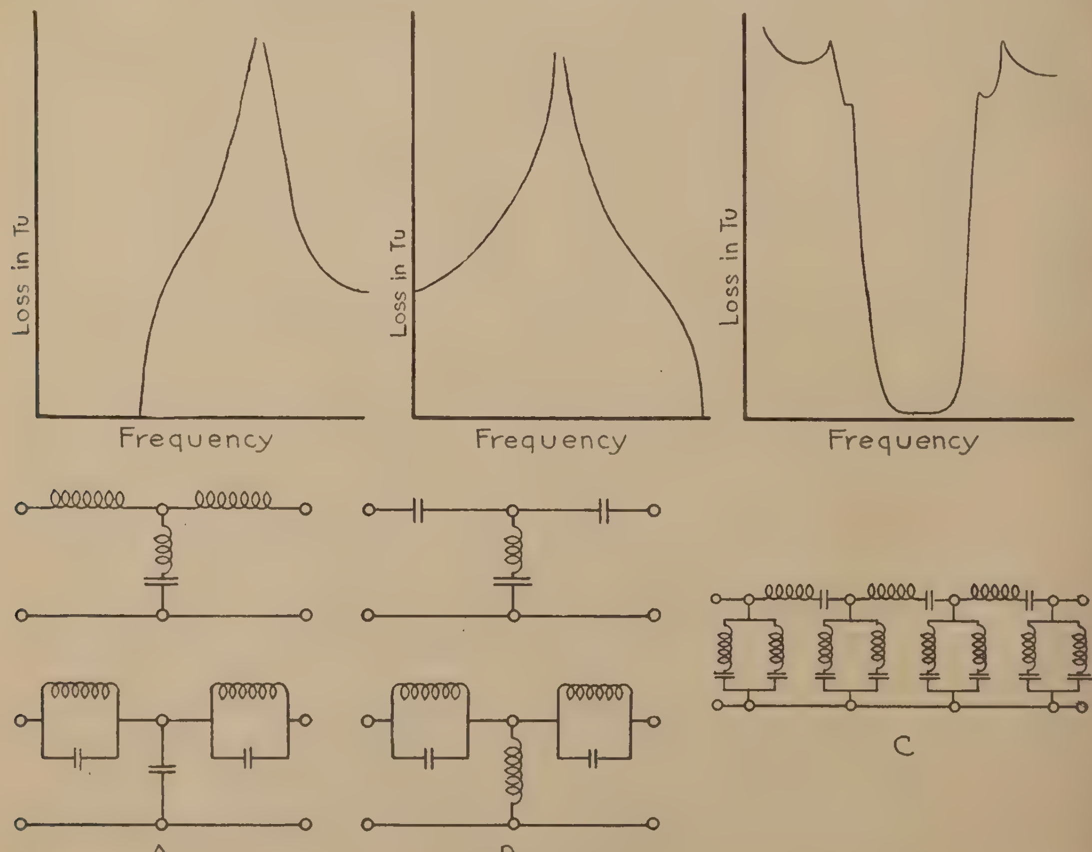



*Fig. 285—Filters.*

peater to a modified "21" type set permits ascertaining what is the maximum gain it can give before the singing point is reached. This gain is a direct check on the effectiveness of the network balance, as a high gain means that at no single frequency within the voice frequency range is there an appreciable dissimilarity between the impedance of the network circuit and the impedance of the line with its associated equipment, thereby assuring proper repeater operation. When the "21" circuit test indicates an improper circuit balance the cause for which cannot be detected from a casual inspection of the line, line equipment, or network equipment, line impedance tests or impedance unbalance tests to be discussed in the next Chapter are relied upon.

### 140. Filters

On the input side of each amplifier of the telephone repeater circuit illustrated in Figure 247 is shown a high frequency filter. This is only one of many uses made of filters in the telephone plant but will serve to illustrate their functions. There are three types of such filters, viz., low frequency or high pass filters, band filters, and high frequency or low pass filters. This particular one belongs in the last category and will pass all important voice current or lower frequencies but will stop higher frequencies in the same way that a loaded circuit stops frequencies beyond the cut-off. The theory of this filter is identical to that of a loaded line with lumped constants. Through proper design and proper selection of the inductance and capacity values it is possible to adjust this cut-off point to almost any desired value. Similarly, low frequency filters may be designed by employing series capacity and bridged inductance instead of bridged capacity and series inductance. Now, two properly designed filters when combined might be used to cut off low frequencies to a certain determined limit and also high frequencies to another determined limit with a "band" between the two limits which would be "passed" with little attenuation. A circuit schematic and attenuation curves illustrating the effectiveness of various filters as frequency "sorting" or "channelling" devices is given in Figure 285.

## CHAPTER XXIV

## ALTERNATING CURRENT MEASUREMENTS IN TELEPHONE WORK

### 141. General Methods for Making Measurements

Though much of the technique regarding electrical measurements of direct currents is equally applicable to measurements of alternating currents, it may be said that in general A.C. measurements are more involved. In direct current work our fundamental measurements are restricted to voltage, current, power, and resistance. In alternating current work, while voltage, current, and power are still the fundamental quantities, their interrelationship is no longer simple but involves the determination of phase, frequency, etc. Again, the measurement of alternating voltages and currents must presuppose some standard wave shape and some supposition as to the basis of measuring a quantity which is ever varying, i.e., we may measure an instantaneous value, an effective value or a maximum value. Furthermore, in dealing with wave shapes other than sine waves we must effect some analysis into a fundamental sine wave and harmonics of this fundamental, in order to analyze the conditions correctly.* These new conditions are responsible for complications incidental to the measurement of the quantities which correspond to those we encounter in direct current work and introduce the necessity for more elaborate and painstaking methods for the complete analysis of current flow. Moreover, it may be said that a degree of instability is inherent in certain of the properties met with in A.C. work whereas in D.C. work this difficulty is not encountered. To illustrate, the direct current resistance of a coil winding remains practically fixed with the exception of minor changes in values due to temperature, etc., while the alternating current resistance of the coil may be less stable due to certain additional factors upon which it depends, such as the magnetic properties of the iron core and the physical relationship of the winding to the iron core, all having to do with certain power losses which in turn affect the resistance to the flow of alternating current.

It is not always the practice in alternating current work, to make measurements with the basic units, i.e., ampere, volt, watt, etc. We may employ as standards other units based either directly or indirectly upon the basic units. For instance, in telephone transmission work it is quite possible to determine the attenuation from the relationship

$$\propto = 2.303 \log \frac{I_1}{I_2}$$

by making current measurements but this method is seldom used in the field. Instead, as we know, the TU with a known attenuation is used as a comparison standard for the circuit in question, and the result is expressed in transmission units rather than as a numerical value of $\propto$.

On the other hand, the instruments designed to measure fundamental quantities are none the less important because apart from their field use, which may be limited in some cases, the same principles of operation employed in these devices are frequently employed in connection with other measuring apparatus. We shall, therefore, discuss first of all the actual measurement of the fundamental alternating current quantities.

*See Appendix IV.

### 142. A.C. Ammeters, Voltmeters, and Wattmeters

Indicating instruments such as ammeters, voltmeters, and wattmeters for alternating current measurements are similar in appearance and in manipulation to direct current instruments but must have certain differences in design. A direct current ammeter, such as was described in Chapter V, if connected in series with an alternating E.M.F. would tend to indicate the instantaneous value of the current in the circuit. Now this value is constantly changing, and in the case of a 60 cycle power circuit, the change is from zero to a maximum to zero 120 times a second, 60 such changes occurring while the current flow is in one direction, and the remaining 60 while the current flow is in the opposite direction. It is not possible for the needle to fluctuate so rapidly and consequently it would stand at zero, not responding to any value of current that might flow through the instrument.

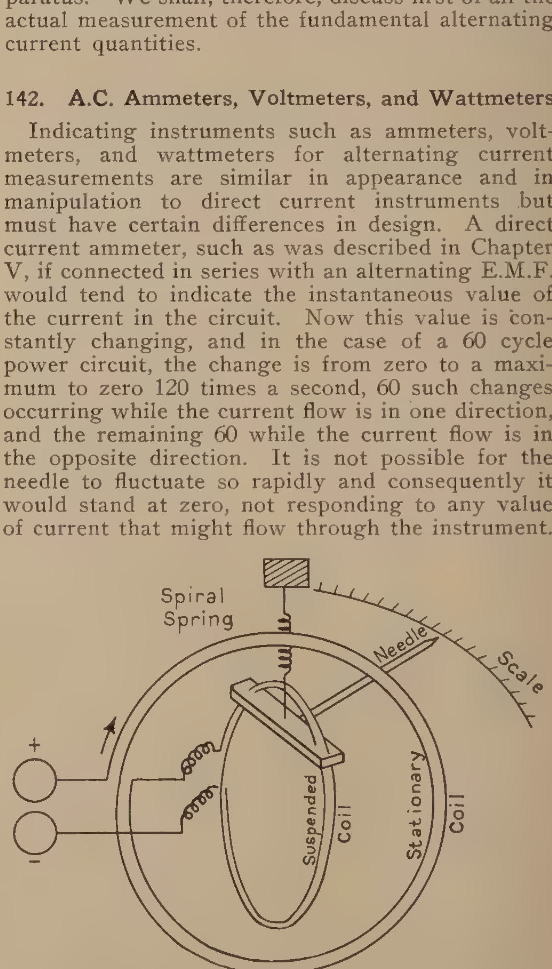



*Fig. 286—Theory of Dynamometer type A.C. Instrument.*

However, by substituting a coil winding for the permanent magnet of the D.C. instrument, we can obtain a definite deflection on the ammeter scale and this indication will depend upon the **effective value** of the current.

This briefly is the fundamental difference between D.C. and A.C. ammeters and voltmeters of this type. The coil winding and the moving element are connected in series so that whenever the current reverses in one there is a similar reversal in the other. Consequently the reaction between the magnetic field of the coil and the current in the moving element is always such as to turn the moving element in the same direction. This is illustrated by Figure 286. Here a movable coil is suspended within, and by means of a spiral spring is held perpendicular to a stationary coil. The magnetic field in the movable coil will tend to allign itself with that of the stationary coil, and the direction of rotation of the movable coil will be the same regardless of the direction of current flow through the two coils in series. If the instrument is a voltmeter it must, of course, have a high resistance; if an ammeter it must have a low resistance, which can be secured by the use of a shunt.

In alternating current work, unless the angle of lead or lag between the voltage and current is known, it is not possible to use an ammeter and a voltmeter for the measurement of power inasmuch as the power equation is—

$$P = EI \cos \Theta$$

instead of $P = EI$

The power cannot, therefore, be determined by simply multiplying together the measured voltage and current values; a wattmeter must be used for accuracy. The A.C. wattmeter likewise employs two coils, but in connecting such an instrument in the circuit, one coil is connected in series so that the current in it varies as the line current, while the other is connected across the circuit so the current in it is proportional to the voltage. Such an arrangement automatically takes care of any phase difference between voltage and current, and the indication of the wattmeter, therefore, depends upon the power in the circuit.

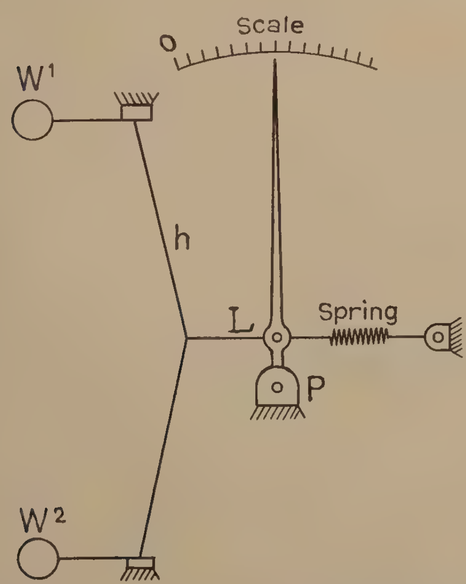



*Fig. 287—Theory of Hot Wire Type A.C. Instrument.*

The ammeter, voltmeter, and wattmeter described in the foregoing are said to employ the "dynamometer" principle. The commercial types of these instruments for alternating current work are usually designed for a single frequency or at best a narrow band of frequencies, and it is not possible, for example, to use the revolving coil mechanism designed for 60-cycle power circuits in connection with telephone current frequencies. Such instruments have considerable inductance which impairs their accuracy at high frequencies. But there are other designs of instruments that are independent of frequency and employ the heating effect of a current as the basis of their operation. The so-called "hot wire" ammeter perhaps best illustrates this series. In Figure 287 **h** represents a small wire which rapidly increases in temperature with an increase in current flowing through it. $W_1$ and $W_2$ are the instrument connections to this hot wire, and both ends of the wire are permanently fixed, though insulated from the case. The middle of the wire is connected through the insulating link L to the needle which is pivoted at P. As in other indicating instruments the needle has a spring attached to it, but unlike other indicating instruments, when the temperature of the wire is above normal this spring tends to make it stand at full scale reading. However, when the hot wire is at normal temperature, it is so constructed as to pull the needle to the zero position. As the current flows through the wire and increases its temperature, the wire expands and the needle is allowed to give a scale reading. The scale is so calibrated as to indicate the effective value of the current flowing through the wire. To take care of changes in atmospheric temperatures the wire is so mounted on the case that the coefficient of expansion between the mountings compensates for the change in room temperature.

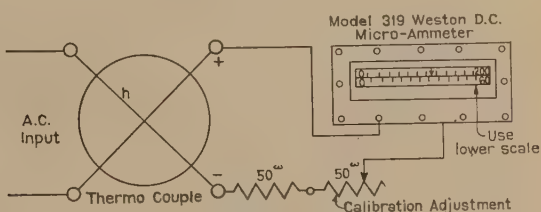



*Figure 288*

Although the hot wire type of instrument is independent of frequency it has other practical limitations. It is not only sluggish in action, since time is required for the **heating** of the wire, but there is danger of **burning out** the instrument because any appreciable overload will produce a temperature great enough to melt the wire.

Neither the dynamometer nor the hot wire type of instrument is suitable for measuring extremely

small alternating current quantities such as are often encountered in communication work. The actual voice current when transmitted over a telephone circuit may vary from less than 10 milamperes at the talking station to 1/10th of one milampere at the receiving station. For the high degree of sensitivity that is required for such measurements amplifying and rectifying devices are often used in connection with **direct current** meters in preference to the types of instruments we have discussed in the foregoing.

### 143. The Use of Rectifying and Amplifying Devices in Connection With Measuring Instruments

The simplest method of measuring high frequency alternating currents, employing a direct current meter, is to use a thermo-couple connected to a sensitive millivoltmeter or micro-ammeter. Such an arrangement is used in the sending circuit of the 4-B transmission measuring set and is illustrated in Figure 288. Here we have a thermocouple, as described in Article No. 53, carrying an alternating current which may vary from zero to

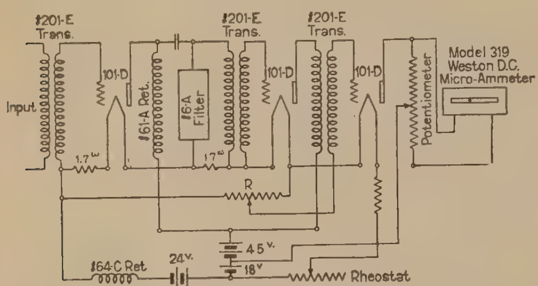



*Fig. 289—Amplifying and Detecting Circuit of The #4-B Transmission Measuring Set.*

60 milamperes and which heats the junction of two dissimilar metals. The direct E.M.F. created at the junction gives a reading on the scale of the sensitive instrument, and this scale may be calibrated for use in connection with the thermo-couple to read milamperes direct. Where current values of less than a few milamperes are to be recorded, the same model or a similar model of instrument with a more sensitive scale may be used in connection with an amplifying and rectifying circuit. Such an arrangement is employed in the receiving element of the 4-B transmission measuring unit. Figure 289 shows this circuit, where current values within the range zero to 200 micro-amperes may be measured. The circuit has two vacuum tubes used as amplifiers and a third vacuum tube used as a rectifier. The negative grid potential for the third tube is adjusted to give the desired rectification by means of a potentiometer connected across the filaments of the first two tubes. Fixed resistances in series with the filaments of the amplifying tubes give the desired grid potentials for the two stages of amplification in this circuit. In order that the indicating instrument will not read the entire plate supply current in the rectifying tube there is a shunt and adjusting potentiometer operated in connection with this meter as shown in the diagram.

In telephone work there are many other testing circuits which employ some form of rectification, or both rectification and amplification, in connection with direct current instruments. Such circuits are employed in connection with the telephone interference factor meter, the 3-B and 6-A transmission measuring sets, the telephone repeater gain measuring set, the impedance unbalance measuring set, etc. The principle of operation is no different in the measuring elements of these instruments than in the 4-B transmission measuring set, but the amplifying and rectifying circuits as well as the type of direct current instrument used may vary in detail. In some cases only one stage of amplification is used, and different voltage values are employed in connection with the operation of the vacuum tubes.

### 144. The Impedance Bridge

In Chapter VI we first encountered the Wheatstone bridge and learned the theory of "balance" which permits us to measure the D.C. resistance of any circuit. Later we saw that the principle of balance can also be applied to alternating currents and

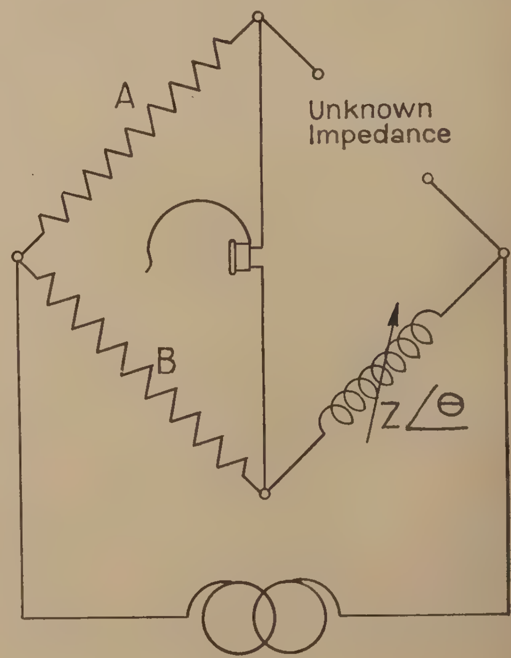
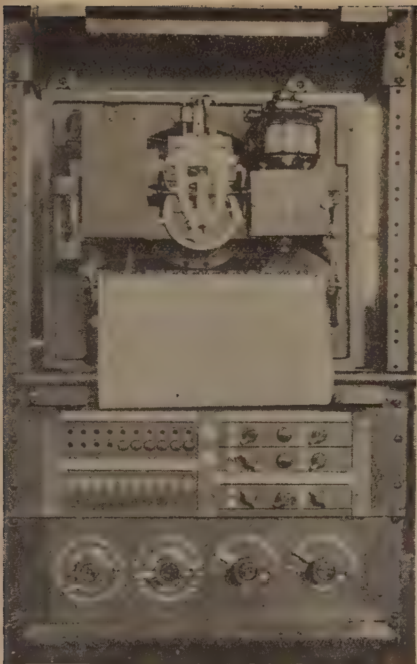
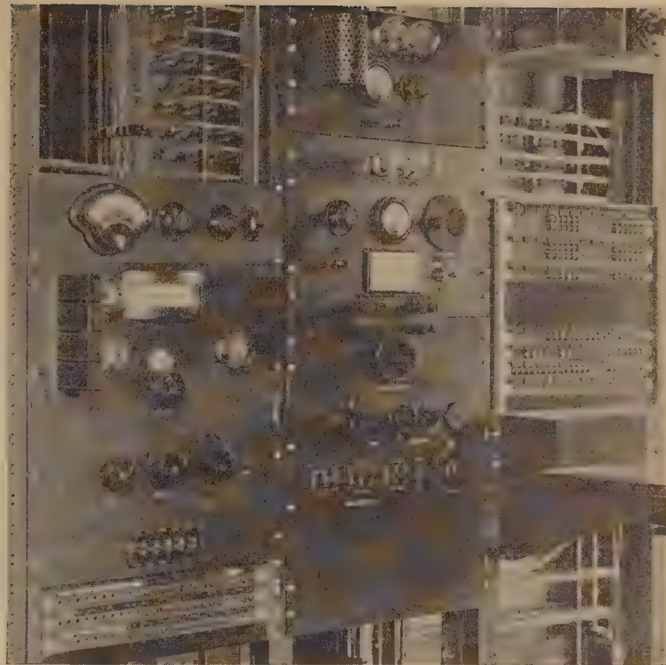



*Figure 290*

in Article No. 104 we discussed briefly an A.C. Wheatstone bridge circuit. In telephone work it is frequently necessary to make A.C. bridge measurements, and to this end we utilize the "impedance



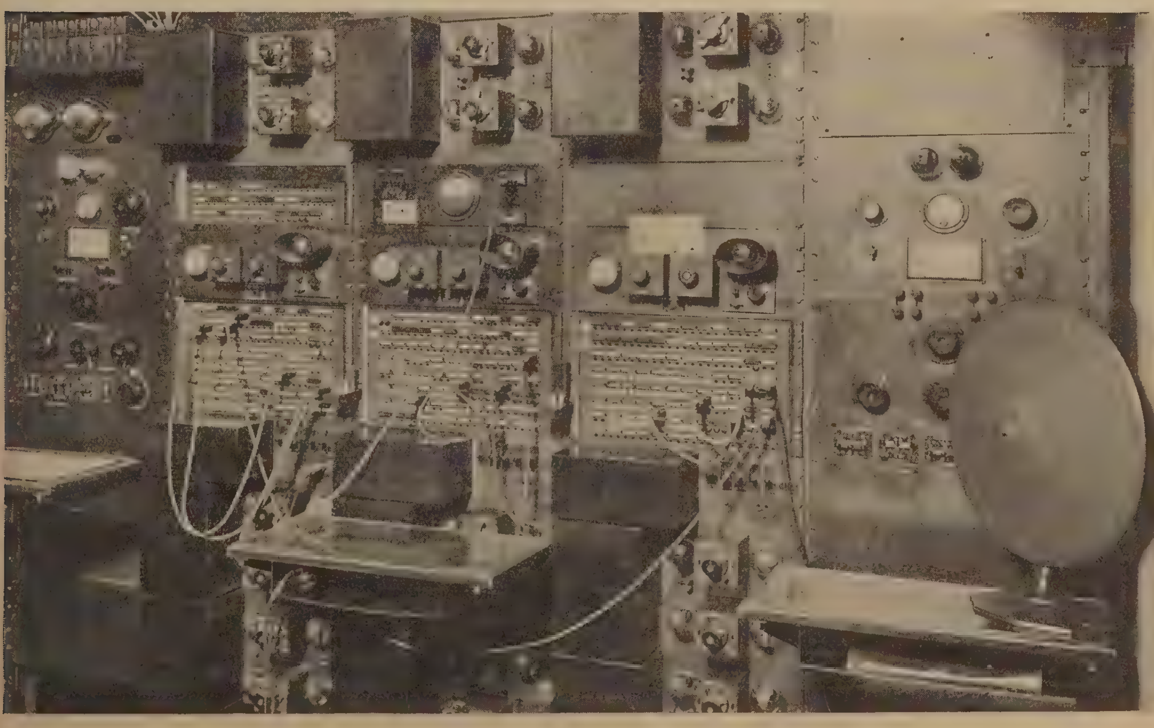


## Transmission Testing and Regulating Apparatus

*Left above*—Close-up of pilot-wire transmission regulator.

*Right above*—Close-up of 6-A transmission measuring set and oscillator.

*Below*—Typical installation of testing and switching apparatus for use in furnishing program supply services.



bridge" illustrated in Figure 290. It can be seen that this is merely a modification of the Wheatstone bridge with an alternating source of E.M.F. substituted for the battery, a telephone receiver (where the frequencies are within the voice current range) substituted for the galvanometer, and a variable impedance substituted for the adjustable resistance arm of the Wheatstone bridge.

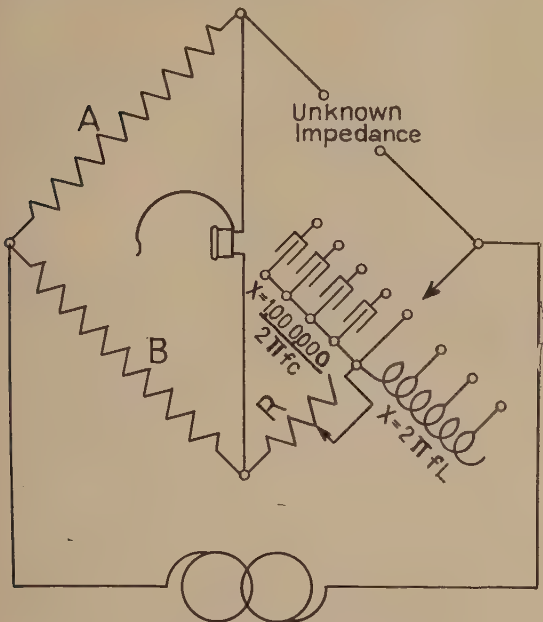



*Fig. 291—Theory of Impedance Bridge with Variable Impedance Arm.*

The similarity here needs no further discussion; but the construction of an adjustable impedance introduces the necessity of having some means of varying either or both the resistance and the reactance. Owing to the phase relations, it would generally be impossible, by merely balancing the number of ohms in the adjustable arm to correspond to the number of ohms of the unknown impedance, to balance the circuit shown in Figure 290 until no tone was heard in the telephone receiver. It follows, therefore, that the variable impedance arm must be adjustable with respect to two distinct components — resistance and reactance, and provision must be made to have the balancing reactance either positive or negative. Theoretically, we might employ a device such as that illustrated in Figure 291. Here we have two distinct adjustments, one of which is a simple resistance and the other of which is a dial arrangement by which the reactance may be made any value, either positive or negative. With the capacity or inductance values known the reactance component can be calculated for any given adjustment from the formula

$$X = -\frac{1{,}000{,}000}{2\pi fC}$$

or $\quad X = \cdot\ 2\pi fL$

as the case may be.

There is a more practicable arrangement, however, which will accomplish the same result as that illustrated by Figure 291. It eliminates the use of the variable capacity and employs only an adjustable inductance in the form of an inductometer.

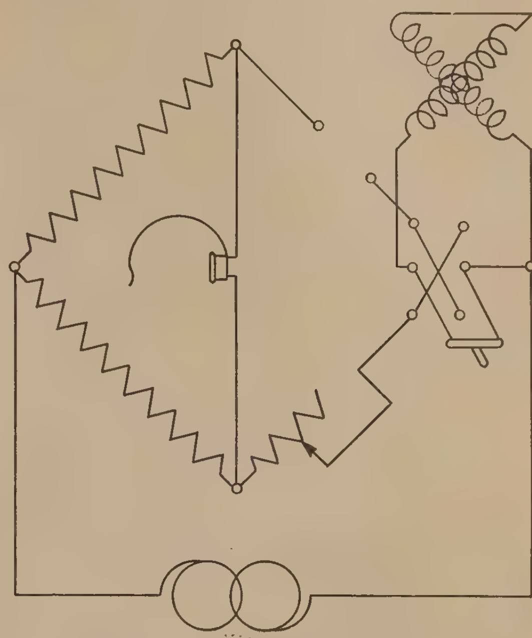


*Fig. 292—Theory of Impedance Bridge with Inductometer and Transfer Switch.*

This is illustrated in Figure 292. The inductometer is a device consisting of two similar coils, one of which may be rotated with respect to the other. Such an arrangement permits of a variation of inductance from almost zero, when the magnetic fields of the two coils oppose each other, to a maximum when the fields aid each other and the inductances add directly. The condenser is eliminated by introducing a transfer switch by which the inductometer may be connected in series with the unknown impedance so as to **neutralize a negative reactance component** rather than balance it. Inasmuch as the inductometer is calibrated in terms of milhenrys or henrys, as the case may be, the reactance component must be calculated by use of the formula—

$$X = 2\pi fL$$

This component will be negative when the switch is so thrown that the inductometer is in series with the unknown impedance, and will be positive when the switch is so thrown that the inductometer is in series with the adjustable resistance arm.

In the actual construction of an impedance bridge, of course, it is not possible to employ an inductometer having zero resistance. It is necessary, therefore, to have a compensating resistance which is similarly connected to switch contacts and will always be in the opposite arm to the one in which the inductometer is connected. Figure 293 is a diagram of connections of the 1-B impedance bridge used in the telephone plant for measuring line impedances. Due to the fact that it is not possible to secure absolute zero inductance with the inductometer, a second fixed inductance is used, which may be switched from one arm to the other. An absolute zero inductance can then be secured by throwing the fixed inductance on one side of the bridge and the inductometer on the opposite side so that the fixed one neutralizes its value on the scale of the other. Since either inductance unit may be switched to either side of the bridge, it can be seen that the reactance values that can be measured range from zero to a value of $\pm\ 2\pi f\ (L_a + L_b)$, where $L_a$ and $L_b$ denote the values of the two units. Like the inductometer, the fixed inductance also has a compensating resistance which is so wired to the transfer switch that it will always be in the proper arm of the bridge to balance the resistance of the coil.

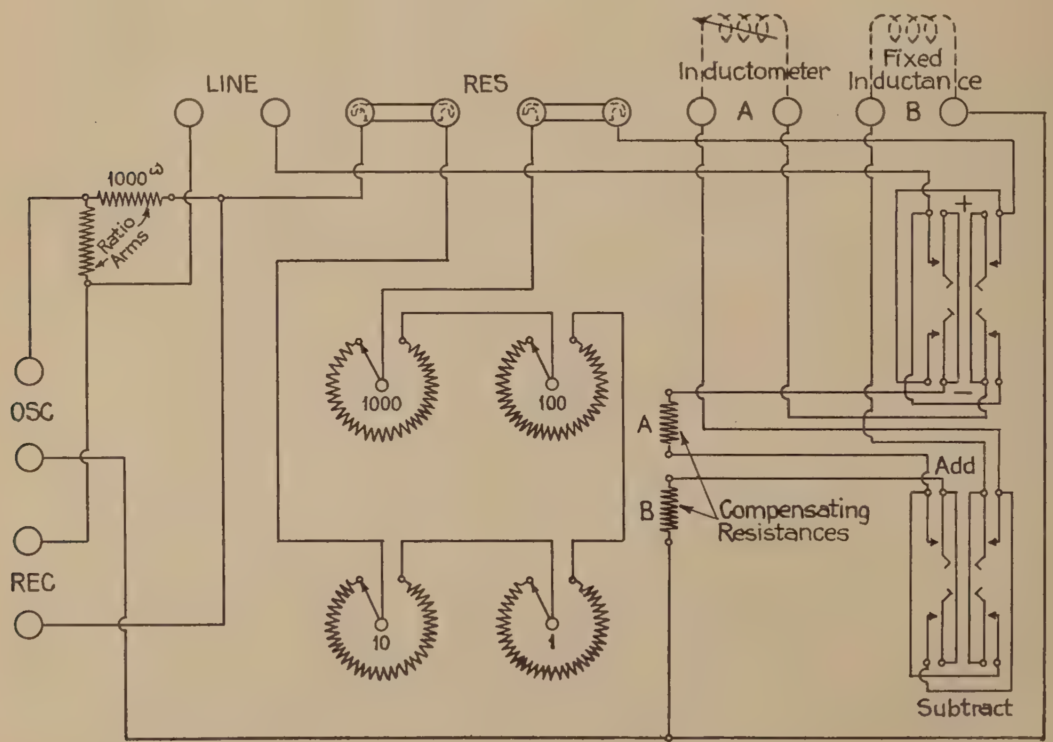


*Fig. 293—Connections of #1-B Line Impedance Bridge.*

A vacuum tube oscillator is used in connection with the bridge as the A.C. supply, and to permit measurements over the entire range of voice current frequencies the oscillator has an adjustable resonant circuit which allows any desired frequency value within this range to be obtained. It is also equipped with a filter for eliminating the harmonics of the particular frequency used, thereby affording a pure sine wave testing current.

## 145. The Capacity Bridge

From the theory of the impedance bridge, it can be seen that it would be quite possible to measure capacity values with this device. However, since condensers are practically pure negative reactances it is more convenient to eliminate the variable resis-

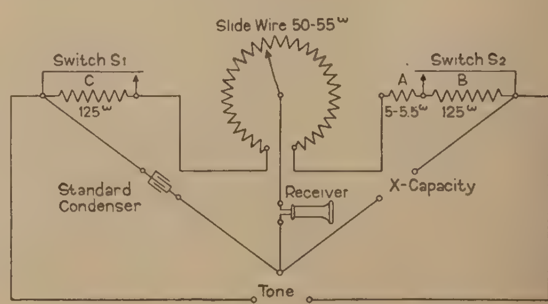


*Fig. 294—Theory of Capacity Bridge.*

tance, thus simplifying the manipulation. Figure 294 shows the impedance bridge when modified to measure capacities and in this form it is known as a "capacity bridge". Here, instead of having fixed ratio arms, we have these arms variable and obtain balance by adjusting these arms until no sound is heard in the receiver. In other words the principle of the slide wire bridge explained in Article No. 38 is employed. In the portable capacity bridge, the scale reading gives the ratio of the resistance arms so the value of the unknown capacity is

$$C_X = \text{Scale Reading} \times C_S$$

where $C_s$ is the capacity value of the standard condenser.

### 146. Line Impedance Measurements

In Chapter XXIII we learned that the successful operation of 22-type telephone repeaters necessitates the use of a balancing network for each line with which the repeater is associated. In maintaining the required degree of balance between the network and the line, measurements throughout the voice range of frequencies are sometimes required in order to check the impedance values and to locate any irregularities in the line circuit that may seriously affect the balance. Here an impedance irregularity means any condition throughout the length of the line that may cause a partial reflection of the electrical wave. From our earlier considerations of wave propagation we know that any wave will suffer both attenuation and phase displacement as it travels along a line, and this is, of course, also true of the reflected wave. Consequently, the magnitude of this wave and its phase position relative to the wave just leaving the generator, will change as it moves from the point of reflection to the sending end. Further, a little consideration will show that the phase of the reflected wave when it reaches the generator will depend on the **time** it takes to travel from the irregularity to the generator, or what amounts to the same thing, on the **distance** from the irregularity to the generator.

For a clearer analysis of the effect of an irregularity on a line, let us resolve the current entering the line into two components, one the current that would enter the circuit if there were no irregularity, and the other the reflected current that is present due to the irregularity. Let us consider the case where the distance from the sending end to the irregularity is such that in this distance there are for a particular frequency an even number of waves. Any current that may be reflected will reach the generator in phase with the component of current entering the line at that point so the resultant line current will be the arithmetic sum of the two.

Now if the frequency is increased slightly, the wave length will decrease so that there will no longer be an even number of waves in the distance from the irregularity to the generator. The reflected current reaching the sending end will not be in phase with the other component and the resultant current will consequently be less than before. If now we continue to increase the frequency we will again obtain a condition such that an even number of waves appear in the given distance, but now there is one more wave than previously. However, as before the two component currents being in phase combine arithmetically to give the resultant current. In other words, the sending end current will vary with frequency, so that if we measure the impedance of the circuit, since $Z = E/I$ we will

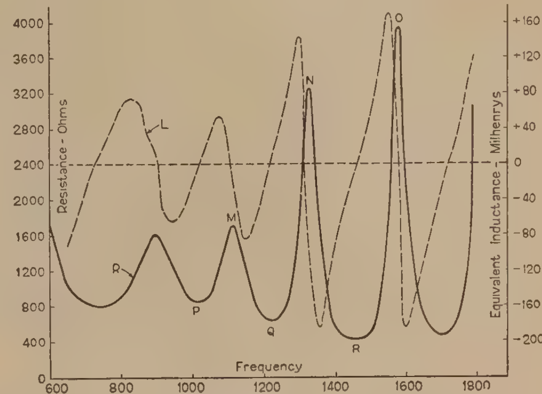



*Fig. 295—Impedance Curve of Circuit with Single Large Irregularity.*

find periodic variations such as appear in the curve of Figure 295. This is a typical impedance curve obtained by making measurements with the impedance bridge on a line having an impedance irregularity. Here points M, N. and O correspond to frequencies where the distance to the irregularity is such that the reflected current is exactly opposite in phase to the outgoing current at the sending end and points P, Q and R to frequencies where the reflected current is exactly in phase with the outgoing current at the sending end.

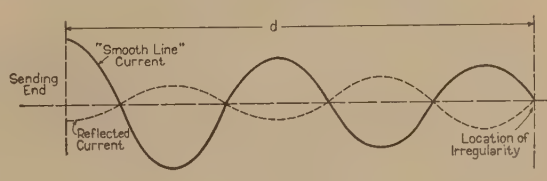



*Figure 296*

Now, such a curve permits a determination of the distance from the sending end to the irregularity by the use of the following formula,

$$d = \frac{W}{2\,(f_2 - f_1)} \qquad \text{.................... (113)}$$

where d is distance to the irregularity, W is the average velocity of propagation of the telephone currents over the particular line in question, which may be taken from Tables XV and XVI, and

$f_2 - f_1$ is the average frequency interval between the adjacent "humps" of the impedance curve. If, in the case of a loaded circuit, we employ the number of "loads per second" for the term W, d will give the number of loading points between the sending end and the irregularity. If we employ miles per second for W, the distance will be in miles, etc.

> **Note:**—Equation (113) may be derived by referring to Figure 296 and setting up two equations with number of wave-lengths and distance as two unknowns. Here the conditions are such that the reflected current is opposite in phase to the "smooth-line" component so the impedance $Z = E/I$ is a maximum. If we increase the frequency, thereby decreasing the wave-length, so there are two and three-quarters waves in the distance d instead of two and one-quarter as shown, we will again have the same phase relation between the two component currents and the impedance will again be a maximum. That is, by changing the frequency so the distance includes an additional half wave, the phase relations are maintained undisturbed. If $f_1$ is the frequency when d includes two and one-quarter waves, we may write
>
> $$d = n \lambda_1$$
>
> where $\lambda_1$ is the wave-length corresponding to the frequency $f_1$ and n is the number of such wave-lengths in the distance d. (In this particular case, $n = 2\frac{1}{4}$). For the second case, where d includes an additional half wave-length, we may write
>
> $$d = (n + \tfrac{1}{2}) \lambda_2$$
>
> But $\lambda_1 = \dfrac{W}{f_1}$ and $\lambda_2 = \dfrac{W}{f_2}$ (from equation (103)
>
> Substituting these values of $\lambda_1$ and $\lambda_2$ in the above equations we have
>
> $$d = n \frac{W}{f_1}$$
>
> $$d = (n + \tfrac{1}{2}) \frac{W}{f_2}$$
>
> Here we have two equations with two unknowns, namely d and n, and since we are not interested in n we will eliminate it; thus
>
> $$n = d \frac{f_1}{W}$$
>
> Whence we have
>
> $$d = \left(d \frac{f_1}{W} + \tfrac{1}{2}\right) \frac{W}{f_2}$$
>
> $$= d \frac{f_1}{f_2} + \tfrac{1}{2} \frac{W}{f_2}$$
>
> or $$d - d \frac{f_1}{f_2} = \tfrac{1}{2} \frac{W}{f_2} = d \left(1 - \frac{f_1}{f_2}\right)$$
>
> from which $$d = \frac{W}{2 f_2 \left(1 - \dfrac{f_1}{f_2}\right)} = \frac{W}{2 (f_2 - f_1)} \quad (113)$$

To illustrate the use of equation (113) let us take a typical example.

**Example:** Calculate the distance to the irregularity on the loaded 104 open wire circuit whose impedance curve is shown in Figure 295.

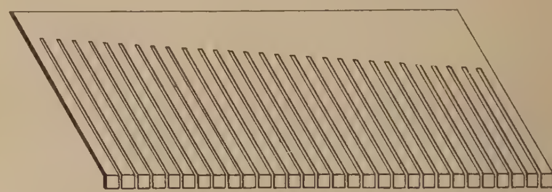


*Figure 297*

**Solution:** On the R curve, we have "peaks" at 890 and 1590 so that $(f_2 - f_1) = 1/3$ (1590-890) $= 1/3 \times 700 = 233$. Similarly from the L curve, $(f_2 - f_1) = 1/2$ (1560-1080) $= 240$. Using the average value of $(f_2 - f_1)$ we have—

$$d = \frac{W}{2 (f_2 - f_1)} = \frac{7410}{2 \times 237} = 13.4 \text{ loads. Ans.}$$

This circuit was made up of loaded and non-loaded facilities and the loaded section was at the sending end. There were 13 loading points between the office and the junction of the two types of facilities.

## 147. Frequency Meters

As mentioned earlier, in alternating current work we must know the value of the frequency and there are several methods of determining it, the one employed in each case depending entirely upon the conditions. For frequency values lower than about 200 cycles a simple vibrating reed device will give direct readings within a reasonable degree of accuracy. The theory of this instrument is illustrated by Figure 297. Here we have a comb shaped arrangement of vibrating reeds of varying lengths, each having a different natural period of vibration. A coil winding is connected to the circuit for which the frequency is to be determined and the core of this coil has long narrow pole pieces of the same length as the group of vibrating reeds. The reeds are inserted in the air gap between the pole pieces. There is a magnetic attraction, therefore, for each reed due to the alternating current in the coil in the same way that there is magnetic attraction for the diaphragm of a telephone receiver. The particular reed which has a period of vibration corresponding to the current frequency will vibrate

but other reeds will not respond to the magnetic pulses. The ends of the reed are alligned under a scale as illustrated by Figure 298, and the frequency can be read by noting the long white line created by the reed vibrating with the greatest amplitude. This form of meter is employed in telephone offices for regulating 135-cycle ringing current.

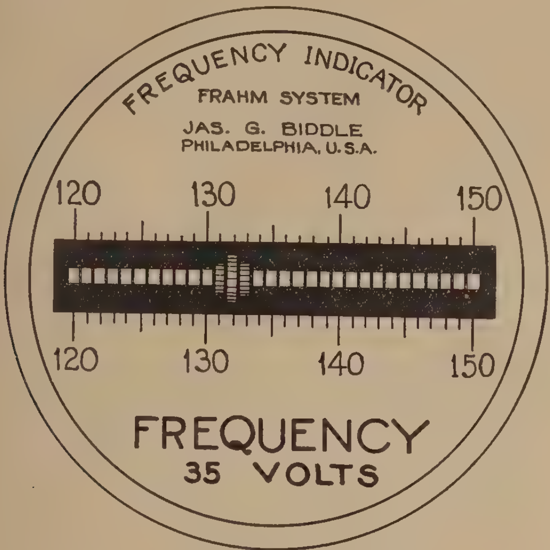



*Fig. 298—Frequency Meter.*

The vibrating reed meter depends for its operation upon mechanical resonance, but for higher frequencies than 200, such as are used in telephone, carrier current, and radio work, electrical resonance is ordinarily employed. In other words, any resonant circuit with adjustable capacity or inductance values can be used for determining frequency. One illustration of such an application is in the case of

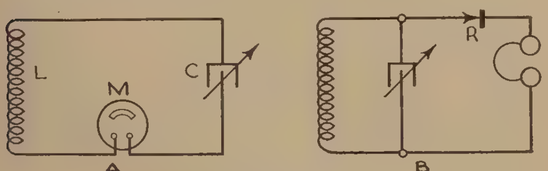



*Figure 299*

the wave meter used in connection with tuning radio transmitting stations. This is shown in Figure 299. In circuit A if an inductance "L" and a condenser "C" are so adjusted as to give resonance, the high frequency meter "M" will give a maximum reading. In circuit B the resonant condition will obtain when maximum sound is heard in the telephone receivers which are connected in series with a rectifying device, "R".

Instead of using the resonant circuit in connection with a meter as illustrated by Figure 299, it may be used in connection with the impedance bridge, as illustrated by Figure 300. Here when the variable capacity which is in series with the variable inductance gives resonance to the impressed frequency it is possible to secure a bridge balance by means of the variable resistance arm alone. This scheme is employed for calibrating vacuum tube oscillators used in connection with the impedance bridge and various transmission measuring devices.

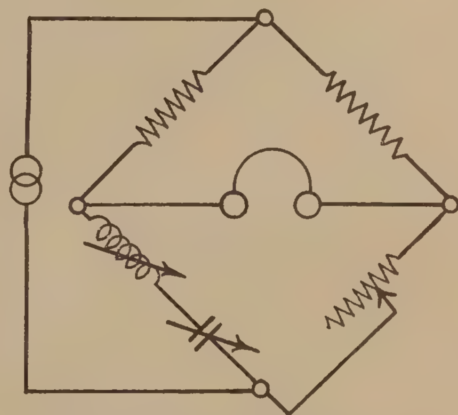


*Fig. 300—Frequency Measurement Using Impedance Bridge.*

Another application of the resonant principle for determining frequency is the resonant wave analyzer which is used to determine the harmonics in power circuits that are objectionable from the standpoint of induced noise in telephone circuits. In other words, the resonant wave analyzer is a form of frequency meter.

## CHAPTER XXV

## TRANSPOSITIONS AND PROTECTION

### 148. Noise and Crosstalk Considerations

One of the factors upon which the intelligibility of a telephone conversation depends is the absence of objectionable noise and crosstalk. If each telephone circuit or each telephone connection that we may consider were isolated from all other telephone circuits or any other electrical circuit whatsoever, we should not expect any potentials to exist in the communication circuit other than those introduced for the purpose of transmission. But this is an ideal or, in fact, a hypothetical condition as every telephone circuit of considerable length comes in close proximity to other telephone circuits, and perhaps circuits carrying electrical energy other than voice current energy.

It is necessary, therefore, that telephone circuits not only be efficient in transmitting electrical energy without distortion and without too great a loss, but also that they be both protected from foreign electrical energy and "balanced", so to speak, against all other electrical circuits. Here when we speak of balance we mean that the circuit must be immune or nearly immune from induced effects. Any two telephone circuits of considerable length that parallel each other and have no transpositions will "crosstalk" to such a degree that the effects may seriously interfere with the use of the circuits. In fact when the first long distance telephone line was built, carrying two adjacent circuits without transpositions, it was hardly possible for the listener at one end to distinguish which circuit was being talked over at the distant end. This crosstalk is the result of two distinct electrical effects, namely "electromagnetic induction" and "electrostatic induction". These effects can be explained best when treated separately.

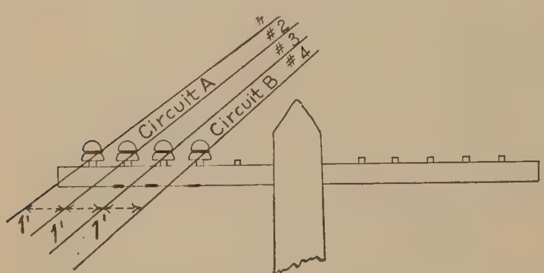



*Fig. 301—Adjacent Telephone Circuits on Pole Line.*

### 149. Theory of Electromagnetic Crosstalk

Let us consider two very long telephone circuits side by side over the same telephone line. These we may represent in Figure 301 as Circuit "A" and Circuit "B". The separation between wires 1-2, wires 2-3 and wires 3-4 will be one foot in each case. The distance, therefore, between wires 1-4 will be three times the distance from wire 2 to wire 3. Let us assume that a conversation is being transmitted over circuit "A" at the same time that a conversation is being transmitted over circuit "B". The theory of electromagnetic induction creating crosstalk in such a case can be better understood by referring to Figure 302.

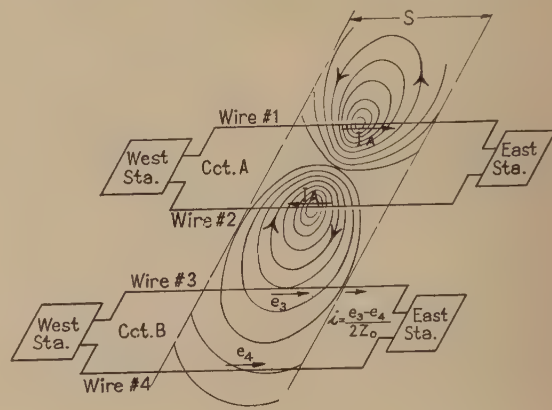



*Figure 302*

For a particular instant the current due to the conversation in circuit "A" is represented by an arrow from west to east in wire 1, a similar arrow with direction reversed but of the same magnitude representing the return current in wire 2. The magnetic field established by such a current is represented by the concentric curves surrounding these wires. These are not exact circles as the magnetic field is denser between the wires than to either side of the wires. Remembering that the current creating this magnetic field is an alternating one, let us investigate the effect at some instant when the current is increasing in value. The lines of force will be expanding and in so doing will cut both wires 3 and 4 but more lines will cut wire 3 than will cut wire 4. We may represent, therefore,

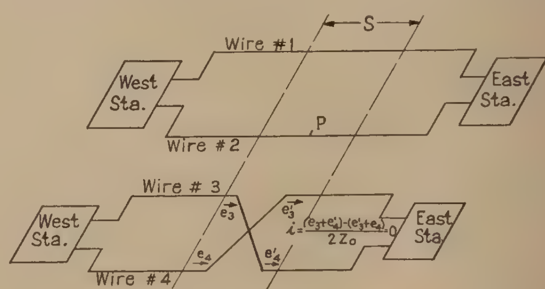



*Figure 303*

the induced E.M.F. in wire 3 by an arrow designated as $e_3$ and the induced E.M.F. in wire 4 by a smaller arrow designated as $e_4$. Now these induced E. M. F.'s are tending to make currents circulate in circuit "B" in opposite directions, but inasmuch as the induced voltage $e_3$ is greater than $e_4$ there will be a resultant which is the difference of the two. In other words, an induced voltage of the value $e_3 - e_4$ will tend to make a current circulate in the circuit "B", and for any small section of the line we might choose we could say that the circulating current due to the induced E.M.F. in that section would be of a value given by the following equation:

$$i = \frac{e_3 - e_4}{2Z_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (114)$$

where the impedance looking toward both the west station and the east station is assumed to be the characteristic impedance of the line, $Z_0$, so that the current in circulating traverses this impedance twice. Now, the summation of all the circulating currents due to the voltages induced in every small section of the line that we might consider will result in current flowing through both the west and east stations, which manifests itself in the form of crosstalk created solely through the influence of electromagnetic induction, or we might say, the electromagnetic coupling of the two circuits.

It is possible to practically eliminate this crosstalk by means of transpositions. By a transposition we merely mean the interchange of the pin positions of the two wires of a circuit. Figure 303 represents a transposition cut in the middle of a section of line we may designate as length "S". Let us assume that this section is the same one considered in Figure 302 which gave us the induced current indicated by equation (114). With the transposition at point P, which we will assume to be in the middle of the section considered, the induced E.M.F. in the wire nearer wire 2 will be broken into two equal parts, as represented by the vectors $e_3$ and $e'_3$ in Figure 303. Likewise the voltage induced in the wire farther away from wire 2 will be broken into two parts, $e_4$ and $e'_4$, and with the transposition as shown the voltage $e_3$ will combine with the voltage $e'_4$ and the voltage $e_4$ will combine with the voltage $e'_3$. The induced or crosstalk current for the section "S" in this case, therefore, will be—

$$i = \frac{(e_3 + e'_4) - (e_4 + e'_3)}{2Z_0} \quad \ldots\ldots (115)$$

but with the transposition in the center of the section—

$$e_3 + e'_4 = e_4 + e'_3.$$

Therefore, the numerator of equation (115) becomes zero and the crosstalk current likewise becomes zero.

**150. Theory of Electrostatic Crosstalk**

We may analyze the crosstalk due to "electrostatic induction" by referring to Figure 304. We have already learned that for every small unit length of each circuit there is a certain capacity between the two conductors of the circuit. Thus we have capacity between wire 1 and wire 2 and capacity between wire 3 and wire 4. But not only do we have this bridged capacity which affects the attenuation and the characteristic impedance of the circuit, etc., but inasmuch as the separation between wires 2 and 3 is the same as between wires 1-2 or wires 3-4 we have the same bridged capacity between wires 2-3. We may represent this by a small condenser of a value "c" as shown in Figure 304. This, however is not the only capacity connection between the two circuits. Due to the geometrical relation between wire 1 and wire 3 there is a capacity between them equal to one-half the value of that between wires 2 and 3 since the separation is twice as great. The same applies to wire 2 and wire 4. In the figure we may represent these capacity relations by small condensers designated as c/2. There is still another capacity value—between wires 1 and 4, and since the separation here is three times that between wires 2 and 3, we can represent this capacity with a condenser designated c/3.

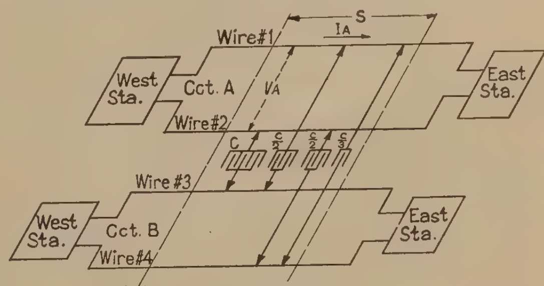



*Figure 304*

Now, as before, let us assume that there is a conversation in circuit "A" giving an instantaneous current from west to east in wire 1 and returning from east to west in wire 2. When this current is flowing there is a difference of potential between wire 1 and wire 2 which we may represent as—

$$V_a = I_a Z_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \ldots (116)$$

This difference of potential between wires 1 and 2 of circuit "A" being an alternating one will tend to cause small resultant currents to flow through the various condenser connections to the wires of circuit "B". The net effect can be best studied by considering the circuits of Figure 304 as a complicated network which can be shown in the form of a Wheatstone bridge as illustrated in Figure 305. A study of the capacity values of the bridge shows that the impedances of the arms are not such as to give a balanced condition and consequently current will flow through the impedances $Z_0$. In other words a current will be set up in circuit "B" and, as in the electromagnetic case, this current will manifest itself in the form of crosstalk at both subscribers' stations of circuit "B".

The use of transpositions is effective in securing a balance against electrostatic as well as electromagnetic crosstalk as may be seen from Figure 303. The transposition in the middle of section "S" will change the capacity relations so that in the Wheatstone bridge circuit of Figure 305 conditions for balance obtain.

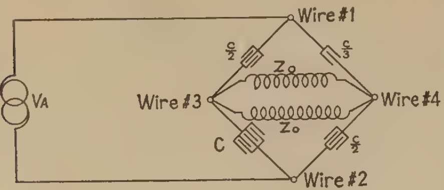



*Figure 305*

## 151. Transposition Systems

The question might arise, Why can't the section "S" represent the entire circuit and a single transposition cut in the middle of circuit "B" be used to eliminate the crosstalk between the two circuits? This is not possible for two reasons; the first reason is that due to attenuation effects the current and voltage near the talking end of circuit "A" are many times as great as the current and voltage near the listening end of the circuit. We, therefore, cannot expect the induced crosstalk on the talking side of the transposition to be neutralized by the much weaker crosstalk on the other side. Furthermore, even if the crosstalk effects were the same, we cannot expect the crosstalk at one end of the circuit "B" to travel to the distant end and neutralize the crosstalk there because there is likewise attenuation in circuit "B".

The second reason why a single transposition in a long circuit will not entirely eliminate crosstalk is due to phase relations. We have already learned that there may be several wave lengths represented in the propagation of the voice current from one station to another over a long circuit. Since crosstalk is entirely an induced effect, its instantaneous value in any small section "S" is going to depend upon the position of "S" with respect to the sine wave cycle of current in the circuit. If "S" were located so that the current or voltage in it had a maximum value, either positive or negative, we could not expect the crosstalk here to be neutralized by the crosstalk in an adjacent section of similar length which might be located near a point where the voltage or current is zero, i.e., changing from positive to negative value. In other words, a single transposition in this case will not be sufficient. It is, therefore, necessary that the transpositions be installed at frequent intervals with respect to the wave length of the propagated current.

This is illustrated by referring to Figure 306. If we could assume for the instant the condition represented by Figure 306-A we should find that the transposition shown would increase rather than decrease the induced effect. A number of transpositions within a single wave length, as illustrated by Figure 306-B, will be more effective but would not entirely eliminate the crosstalk unless the wave form were such as that shown by the broken dotted line. By increasing the number of transpositions the dotted curve becomes more nearly coincident with the solid curve, and there is accordingly a definite number of transpositions per wave length which gives sufficiently close coincidence for practical purposes.

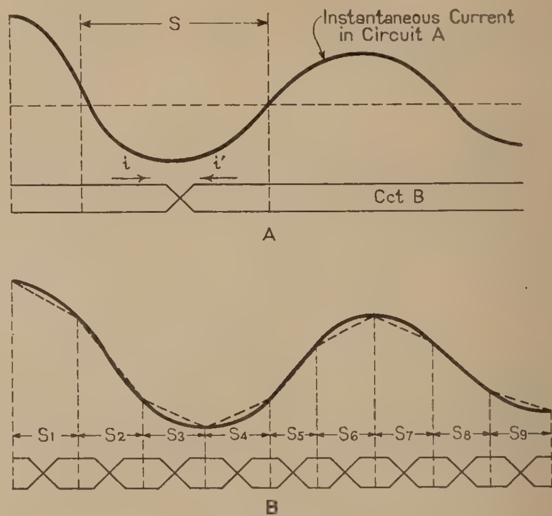



*Figure 306*

In the foregoing discussion of transposition theory we have taken only the case of two adjacent physical circuits on a pole line and we have been concerned with eliminating the crosstalk between these two circuits only. If a third circuit were added the problem would become more complicated and it would be necessary to install additional transpositions in order to balance out, so to speak, the crosstalk for any combination of two circuits. Furthermore, if certain circuits on the line are phantomed, the phantom circuit itself must be considered and transposed with respect to all other circuits as though it were a simple physical circuit. Here we must obtain balance, not only between the phantom and adjacent circuits but also between the phantom and its own side circuits; in fact the three circuits of a phantom group afford the most sensitive layout from the crosstalk standpoint. This requires a mechanical arrangement of the wires to provide not only for the crossing of one wire over another but also for crossing the two wires of one side circuit over the two wires of the other side circuit to effect a phantom transposition, illustrated in Figure 307. Such phantom transpositions also afford opportunities to transpose the side circuits and accordingly we have the various types of phantom transpositions which are shown in Figure 308. Here type #1 gives a transposition in the phantom

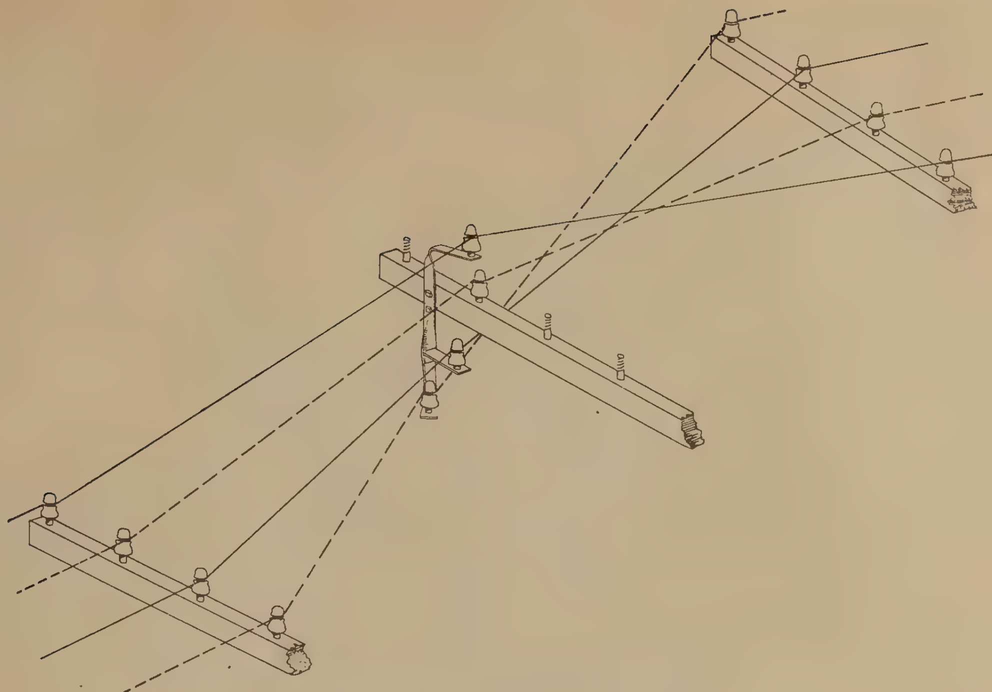


*Fig. 307—Type 1 Phantom Transposition.*

and in both side circuits; type #2, in the phantom and in the side circuit taking the low number of wires, looking in the direction of line numbering; type #3, a transposition in the phantom and the other side circuit; and type #4, a transposition in the phantom but no transposition in either side circuit.

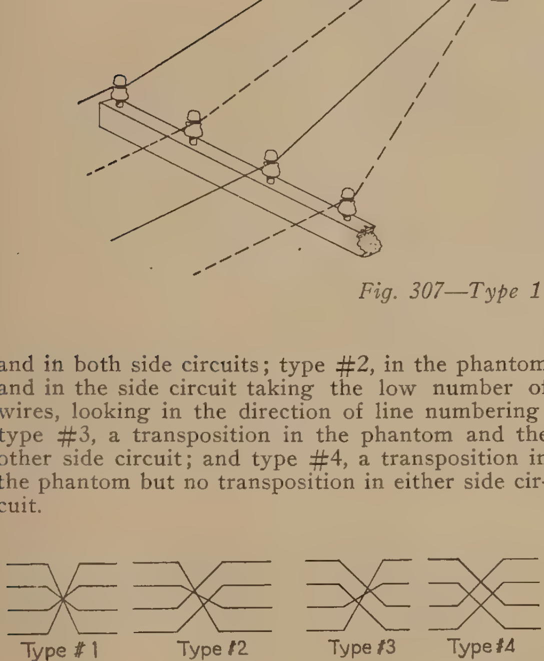


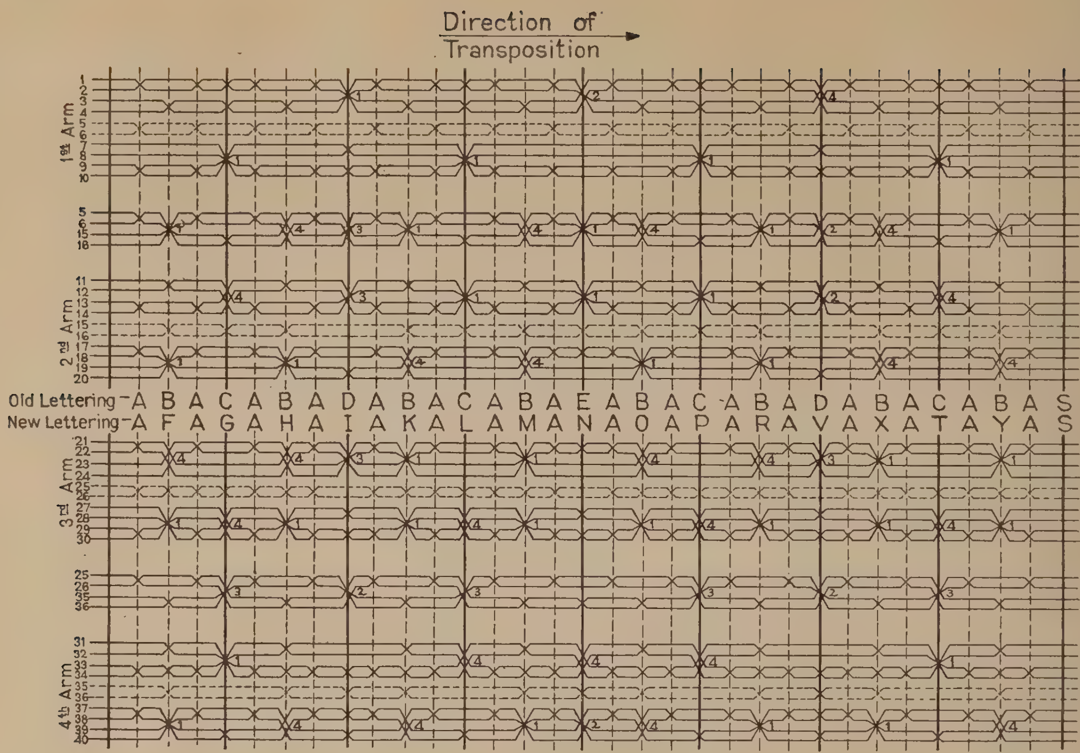

*Figure 308*

In the Bell System, transposition layouts have been carefully engineered to meet practically all conditions. In the first place, for voice current transmission, complete transposition balance must be secured in each section of open wire line 7.88 miles in length. This is necessary inasmuch as the loading coil will cause a shift in phase relation and consequently each section of line must be balanced from the standpoint of crosstalk between adjacent loading coils. Furthermore, for reasons we already have considered, all circuits whether loaded or not must be balanced in comparatively short sections. It is the practice of this Company where a line is not exposed to power or other electrical circuits to employ the "Standard" transposition section which is shown in Figure 309 for a 40-wire line having the ideal layout illustrated by Figure 310. This serves to illustrate a typical transposition section. Of course, if the layout of the phantom groups does not conform to the ideal, there are certain modifications in the number and arrangement of transpositions. Furthermore, the "Standard" section must be supplemented with shorter sections ordinarily referred to as the X, Y, and Z series for use at junctions or at the end of lines where the distance is too short for a standard section. No attempt will be made to give all the standard transposition layouts in this Chapter, but Handbook Specifications or the Operating and Engineering Department's notes on "Transmission Practices" may be referred to for complete information.

### 152. Induction from Foreign Wires

The entire system of transpositions covered in the foregoing is engineered primarily for the elimination of crosstalk coming from induction between adjacent telephone circuits rather than for the elimination of noise due to foreign wires. But it is essential that a telephone circuit be immune not only from crosstalk but also, within reasonable limits, from noise as well.

Noise may be created in a telephone circuit by any induced effects from other electrical circuits where such effects manifest themselves in currents within the range of telephonic frequencies. As an illustration, a power transmission line paralleling




Notes: Dotted lines indicate transpositions in pole pair when Vertical Phantom is not created. Otherwise, diagram covers phantom combinations only. For transposition layouts other than for ideal pin number arrangement of phantom groups and for other than Standard Section etc. See Handbook Specifications.

*Fig. 309—Standard Transposition Section Wires 1-40 for Normal Phantom Combinations.*

a telephone line for any appreciable distance may be a serious source of noise. Although the fundamental frequency for power transmission is usually 60 cycles, due to imperfections in the wave form, it may have harmonics within the telephonic frequencies. The energy transmitted by the power line may in some cases be as great as from 10,000,000 to 100,000,000 watts, and even the energy in the form of harmonics may be as great as 1,000 to 10,000 watts. On the other hand the energy being transmitted by a telephone circuit may be as small as 0.00001 watt. We might, therefore, expect inductive interference from the power line even for a short parallelism at a considerable distance away, due to this extreme ratio of the two quantities of energy. The presence of noise in telephone circuits coming from such sources has a serious reaction upon the telephone service. An amount of noise that might of itself be considered as small may appreciably reduce the intelligibility of the conversation and in addition annoy the subscriber. This effect is going to depend upon both the volume of the noise and upon the frequency.

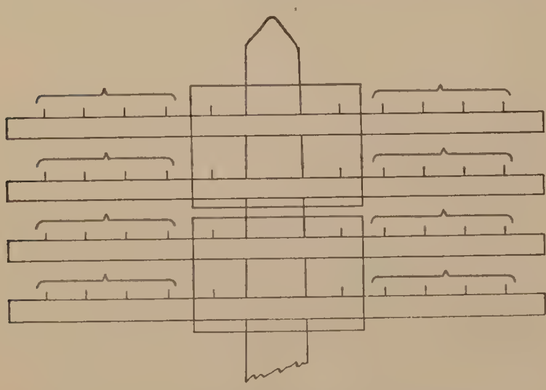


*Fig. 310—Ideal Phantoming Arrangement for 40-Wire Line.*

Figure 311 shows a series of curves which illustrate the interfering effect of noise at different frequencies. There are three methods of determination used which accounts for the three curves, but it will be seen that the results of the various methods check within reasonable limits.

In practice there are two remedial procedures for lessening noise on telephone circuits:—

a. Keeping all circuits of the telephone line well balanced.

b. Engineering remedial measures for each specific case of exposure which may involve special sections or types of transpositions in both the telephone and power lines.

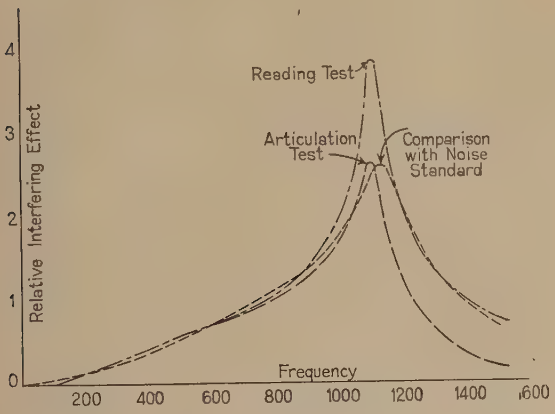



*Fig. 311—Relative Interfering Effect of Single Frequency Currents.*

On account of the highly specialized nature of that telephone work having to do with the engineering of remedial measures for power exposures we shall limit our discussion here to the maintenance of well-balanced telephone circuits and the theory of balance as related to both noise and crosstalk.

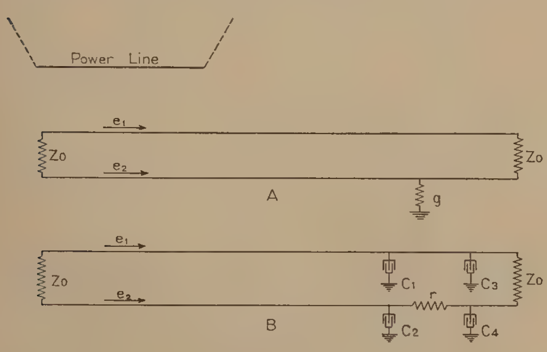



*Figure 312*

To illustrate the necessity for a high degree of balance in the telephone circuit which may be exposed to a power line let us refer to Figure 312-A. Here we have illustrated a section of line exposed to a paralleling power line. Let us assume that this section of line throughout the exposure is properly transposed so that the voltage to ground induced in one wire is equal and opposite to that induced in the other wire, or that $e_1 = e_2$ and the current that would circulate in the line due to these opposing voltages would be zero, provided the two wires were balanced with respect to ground or with respect to all other foreign conductors. Now let us note the effect of leakage to ground somewhere along the wire (not necessarily along the exposed section, however) as represented by the conductance g. The induced E.M.F., $e_2$, will cause a current to flow through the conductance g to ground, or the conductance g will, in effect, shunt this current to ground. On the other hand, the voltage $e_1$ will cause a current to flow to ground through the conductance g, but in so doing it will flow through the impedance, $Z_0$, thereby causing noise at the distant station. The degree of seriousness of the noise produced will depend, of course, upon the magnitude of the unbalance current flowing through $Z_0$, and this will be controlled by the value of the conductance g. It should be noted, however, that poor insulation is not of itself necessarily a cause of noise; even though the insulation of the telephone pair is very poor, if the leakage to ground is the same for both wires of the pair, the currents induced in the two conductors by the power line will still balance out. It is the presence of **unequal leakage to ground** as between the two conductors of the pair that is responsible for the unbalance current through the circuit terminal.

Not only will a leak g from one conductor to ground result in a noisy line even though well transposed against the power exposure, but any other form of unbalance will likewise make a line noisy. Figure 312-B represents a section of exposed line where there is more resistance in one wire than the other due, for example, to a defective sleeve joint. This resistance unbalance is represented by r. Each unit length of each conductor of the circuit has capacity to ground and capacity to other conductors in the same way that there is bridged capacity from one wire to the other. These capacities to ground are represented by condensers $C_1$, $C_2$, $C_3$, and $C_4$. Now the induced E.M.F. in wire #1 which we shall call $e_1$ will cause a current to flow to ground through the condensers $C_1$ and $C_3$. Similarly, the induced E.M.F. $e_2$ will cause a current to flow to ground through condensers $C_2$ and $C_4$. But because of the presence of the resistance r in series with the condenser $C_4$ the current flowing to ground in these cases will not be the same as for wire #1. Consequently, there will be an unbalanced current around through the impedance $Z_0$ to $C_4$, which will reach the subscriber's station, causing the line to be noisy as in the case of a leak to ground. It may be stated, therefore, that transpositions are wholly effective in balancing the wires of a circuit against either crosstalk or noise interference only when the conductors of the line are in all other respects electrically equal or balanced throughout their entire length.

### 153. Capacity Unbalance in Cables

In a telephone cable the two conductors of each pair forming a talking circuit are twisted together and each half twist forms what might be called a transposition. If two pairs are to be used as the

side circuits of a phantom, these are in turn twisted together and the four conductor combination is called a "quad". A quad corresponds to four wires of an open wire line which are transposed for phantom operation. A telephone cable having "quadded" conductor combinations is called a "quadded" (or "duplex") cable to distinguish it from an ordinary (or "simplex") telephone cable. In the "layup" of the cable core there are uneven lengths of twists in various cable pairs and also an alternate right and left spiralling of the various layers of pairs, all of which tend to increase the immunity of the twisted conductors from crosstalk and noise due to inductive effects.

From the standpoint of electromagnetic effects crosstalk or noise in cable circuits is not serious since the greatly decreased separation of conductors lessens the electromagnetic induction. On the other hand the decreased separation greatly increases the capacity between all combinations of conductors and this together with their proximity to the cable sheath increases their capacity to ground. As a result each circuit's sensitiveness to electrostatic crosstalk is increased.

In cable, therefore, we are concerned for the most part with electrostatic crosstalk coming from unbalanced capacity relations. Even with the most careful layup of the core there have not been developed practicable manufacturing methods which would produce cable for long distance service entirely free from inherent capacity unbalances which are sufficiently serious to cause crosstalk or noise.

During the installation of all long toll cables and all "quadded" toll entrance cables of appreciable length it is necessary to so splice the various cable lengths as to eliminate or greatly reduce the various capacity unbalances. This is done by making measurements with a capacity unbalance set on lengths of cable in each direction and so splicing the quads at the junction of the two lengths that the unbalances are neutralized. In this case the splice itself becomes a "kind of transposition scheme". The capacity unbalance set and its use will not be described here but is thoroughly covered in the Company's standing instructions.

### 154. Miscellaneous Circuit Balance Requirements

From the foregoing we have learned that in all telephone work the two sides of the talking circuit should be as nearly identical electrically as possible, and should have the same capacity relations to ground or to other external conductors. This accounts for the use of twisted conductors in substation wiring as well as in all cable circuits, and also for the use of carefully balanced windings for all apparatus that must be connected in series with the line circuit as, for example, the bridge transformer of the telephone repeater. Throughout the entire telephone plant there is perhaps no other maintenance consideration more important than the balance of telephone circuits to prevent noise and crosstalk. Some of the more common causes of unbalance are as follows:

a. Loose or defective connections, including defective relay contacts, unsoldered connections at distributing frames, high resistance sleeves, poor fuse connections in cable boxes, defective cable pair splices, unsoldered bridle wire and loading coil lead connections, etc.

b. Unbalances in line windings of repeating coils used as simplex or phantom sets.

c. Unbalances in windings of 5-AA retardation coils used in the composite set and unbalance in capacity value of composite sets, particularly series capacity.

d. Unbalance in resistance, inductance, or capacity of loading coil windings.

e. Poor line insulation.

f. Transposition errors (regardless of whether in exposed or unexposed section).

g. Improper heat coils or poor contacts between heat coils and protector springs.

### 155. Principles of Protection

Thus far little has been said about the protection of telephone lines against lightning or against power lines where excessive voltage and currents reach the telephone line both by direct contact, leakage, or through induced effects. The long distance plant, extending as it does to many sections of the country, forming a widespread network of conductors, is inherently subject to many electrical hazards and the use and maintenance of various forms of protection, although not primarily required for transmission, is of first importance. We might classify the more common disturbing sources against which telephone and telegraph circuits must be protected as follows:

a. Lightning and other atmospheric disturbances.

b. Ground potential differences between various localities which may be caused by natural disturbances or by power systems.

c. Contact or an insulation leak between power lines and telephone wires.

d. Induced voltages sufficiently large to endanger plant as well as create noise (from power parallelisms).

e. Sources of energy used to operate the circuit itself which may cause currents greater than parts of the circuit are designed to carry, in case of a trouble or some other abnormal condition of the circuit.

f. High powered radio sending apparatus.

Practically every telephone circuit in the plant must be equipped with some form of protection, and in general it may be said that protective apparatus must be sufficiently sensitive to operate before the class of the plant which is being protected is damaged by the disturbing source, and on the other

A

# OUTSIDE PLANT

*Left*—Cable and aerial bare wire on same pole line.

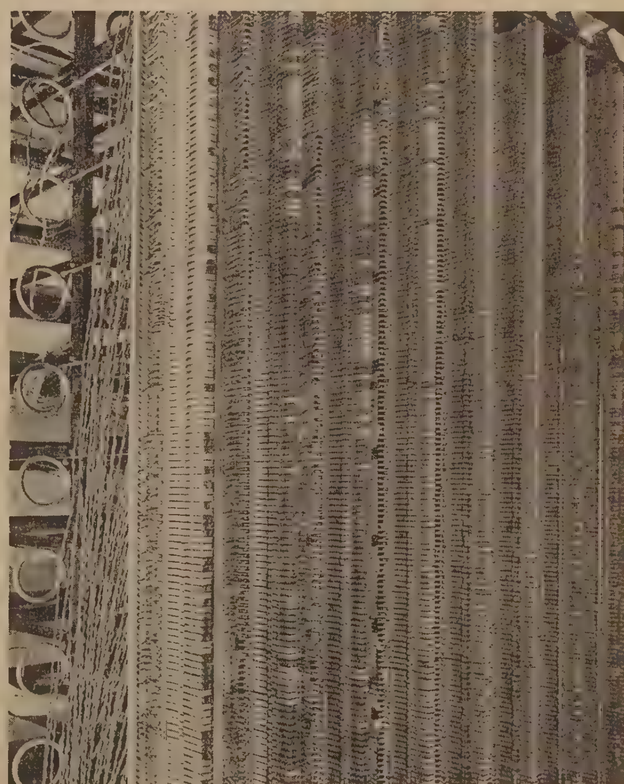
*Below*—Paralleling cable and aerial bare wire lines. Transposition pole in foreground.

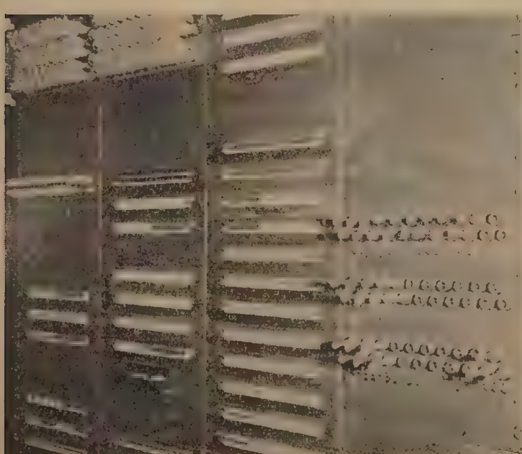
B

# PROTECTION

*Right*—Open space cut-outs and heat coils mounted on distributing frame in central office.

*Below*—Standard alarm type fuse and heat coil protectors for central office circuits.





hand, must not be so sensitive as to cause an unnecessary number of service interuptions.

In the design and use of various standardized methods of protection consideration must be given to whether it is preferable to open the telephone circuits or to ground them. In some cases one is preferable and in other cases the other is preferable. Furthermore, there is a time element to be considered in all protection. The disturbing electrical source may be transient in its nature, occurring with great suddenness and doing considerable damage almost instantaneously, or it may be constant requiring some time to damage the plant because of the heat it creates. The majority of protective devices work on the principle of grounding the circuit so that the ground connection is, for protective purposes, of first importance. There must be installed ground leads free from bends, run as directly as possible, and having low resistance to ground at all seasons of the year.

There are many forms of protective devices standard for use in the Bell System, but in general these can be divided into three classes:

a. Those which open the circuit in case of heavy current; for example, fuses.

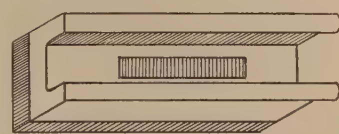
b. Those which protect against excess voltage particularly those from high frequency or lightning discharges by providing an open space cut-out to ground.

c. Those which protect against currents slightly in excess of the currents which the circuit is designed to carry, in case the currents exist for an appreciable period of time.

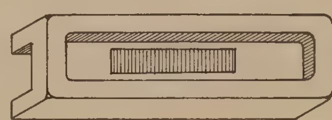
Taking the above devices in order, the principle of operation of the fuse is based upon the melting of some alloy at a low temperature and the opening of the circuit when the current reaches a value in excess of the fuse's carrying capacity. A fuse is usually constructed with a small wire or ribbon of the alloy, either encased in a fireproof container or arranged for mounting on fireproof panels. It may or may not have a special alarm feature. **Where fuses are used in connection with other protective devices that close the circuit to ground, the fuse should always be on the exposed side of the other protective device**; for example, a fuse in a cable box should be on the line side of the open space cut-out. If it were not on the line side, in case of contact with a power wire carrying a very heavy current the operation of the cut-out due to the voltage of the power line might permanently close a circuit from the power wire to ground over the telephone wire and the amount of current carried by the telephone wire would be greater than its capacity, thereby damaging it.

The first requisite of the next type of protective device, the open space cut-out, is that its operating voltage be less than the breakdown voltage of the weakest point in the circuit which it is designed to protect and greater than the maximum working voltage. Again, it is very desirable that its design be such that it will restore the circuit to service after normal operation. However, for very heavy disturbances such as discharge of lightning this cannot always be insured and it may be desired that the open space cut-out give the circuit a permanent ground.

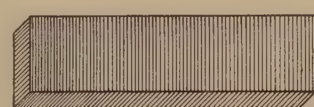
There are several types of open space cut-outs which are very common in the Long Lines plant. One of these is the T-533D arrester which is used for protecting loading coils. This arrester is for use on open wire lines and consists of a small cylinder about which are four other concentric cylinders. The space between the cylinders is such that lightning discharges will leap across this space before puncturing the insulation of a line loading coil. The operating voltage of this type of protector is not sufficiently low to allow of its use for the protection of the ordinary underground and submarine cable. It can be used, however, to protect special high dielectric strength cables.



Nº 26 and Nº 27 Protector Blocks.



Opposite side of Nº 27



Nº 26 - Plain Carbon Block

*Figure 313*

The standard form of open space cut-out used at subscriber's stations, in central offices and at the junctions of cable and open wire is illustrated in Figure 313. It consists of two accurately gauged carbon blocks having a separation of three thousandths of an inch, one of which is connected to ground and the other to the wire to be protected. As shown in the figure, one of the blocks is much smaller than the other, and is mounted in the center of a porcelain block. It is secured in this position by means of a cement which in case of excessive arcing between the carbons will melt, thus permitting the smaller block to make direct contact

with the larger and so permanently connect the telephone wire to ground.

The heat coil is the standard protective device for "sneak" currents. It should always be on the unexposed (office) side of either fuse or open space protection for the same reason that the open space cut-out should be on the unexposed side of the fuse because when the heat coil operates it ordinarily gives a connection to ground. It should also be on the unexposed side of the open space cut-out inasmuch as it contains a coil winding which may present a considerable reactance to lightning discharges, thus preventing the proper operation of the open space cut-out. On the other hand, if installed on the unexposed side it will aid proper operation.

The heat coil in its construction consists of a small coil of wire secured to a metal pin as an axis, this pin being imbedded in an easily melting alloy. The coil is designed to melt the alloy when the current passing through it becomes appreciably greater for any length of time than that for which the circuit is designed. Upon melting the alloy, a spring presses the metal pin until contact is made with a ground plate thereby grounding the circuit. There is an appreciable time interval required, however, for this to take place and the heat coil does not give instantaneous protection. It does give, however, a very sensitive form of protection with respect to the narrow margin of current above that for which the circuit is designed to operate. Heat coils are also used in telegraph battery taps, in which case, however, their operation opens the circuit instead of grounding it.

There are several other forms of protection such as those for mitigating the effects of electrolysis, etc., but since these are of special nature they will not be discussed here.

# CHAPTER XXVI

## CARRIER CURRENT SYSTEMS

### 156. The Principles of the Carrier System

Carrier systems were mentioned in our discussion of telegraph circuits in Chapter XII. The carrier principle is also used in telephone transmission and in either case the object is the simultaneous, independent transmission of several messages over a single circuit, usually without affecting the circuit's ordinary message carrying capacity.

The term "carrier" derives from the fact that alternating currents of certain selected frequencies are employed, in a sense, "to carry" the message. More specifically, the variations of current making up the telephone or telegraph message are impressed on the carrier current and are transmitted over the line by currents of frequencies of the order of the carrier frequency rather than those of the initial message current. In other words, the carrier current acts to shift the frequencies of the message currents to a different range, the position of which is usually above the maximum normal voice current frequency and dependent on the frequency of the carrier itself. It is well to note, however, that we cannot reduce the total number of frequencies (that is, the total width of the frequency band) included in the original message—we can only change its position in the frequency "spectrum". We might, for instance, shift the 1800-cycle band of voice frequencies between 200 and 2,000 cycles to a band of the same width between, say, 16,000 and 17,800; or the band of telegraph frequencies between zero and 25 cycles to a band between, say, 475 and 500 cycles, but the message must always occupy at least its initial amount of space in the frequency spectrum, no matter how it is transmitted over the line.

If now we select several carrier frequencies far enough apart so that the message currents which we next impress upon them will not interfere with each other, we may transmit the several carriers, with their impressed messages, together over a single circuit just as independently for practical purposes as if a separate circuit were provided for each. Then, provided we can find a way to select the message bearing carrier currents at the receiving end of the circuit and take from them the message currents in their original form, we have a system that will handle simultaneously as many messages as we have carriers. The first problem is solved by the use of filters, and the second by a process similar to that necessary for impressing the messages on the carriers. The steps required for accomplishing our result may be summarized as follows:

1. Providing by means of vacuum tube oscillators, or otherwise, the currents of different selected frequencies to be used as carriers.

2. Impressing upon each carrier the message current from the terminal telephone or telegraph station. This process is called **modulation.**

3. Separating or selecting the several modulated carrier currents at the receiving end by means of **selecting circuits** known as **filters.**

4. Separating or restoring from the selected carrier current the original message current for transmission to the receiving terminal telegraph or telephone station. This process is called **demodulation.**

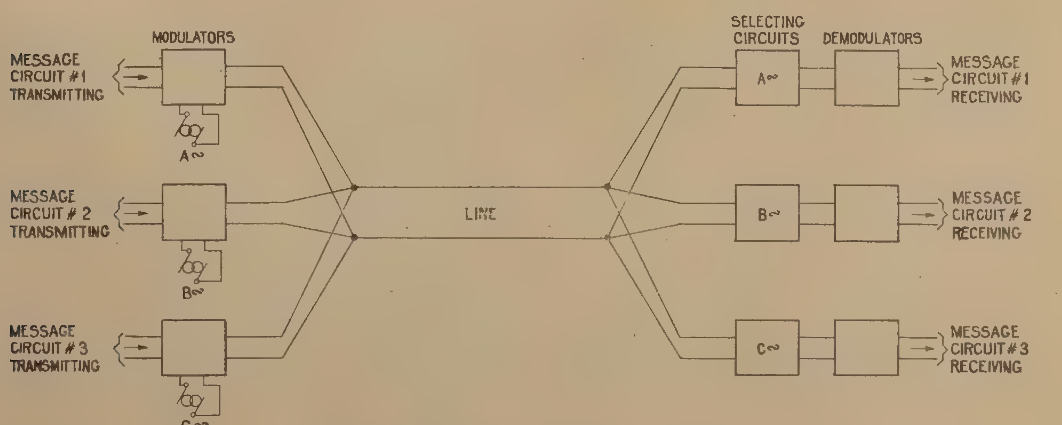
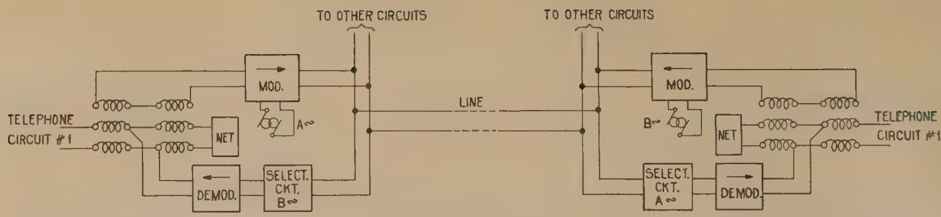
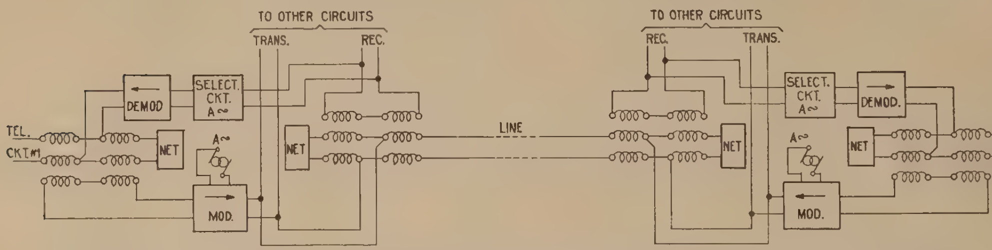



*Fig. 314—Principle of a Carrier System*



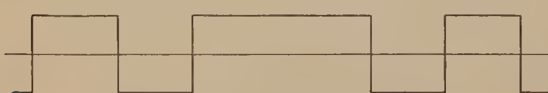

**TWO-WAY OPERATION USING SEPARATE CARRIER CHANNELS FOR TRANSMISSION IN THE TWO DIRECTIONS**




**TWO-WAY OPERATION USING THE SAME CARRIER CHANNEL FOR TRANSMISSION IN THE TWO DIRECTIONS**

*Fig. 315—Methods of Obtaining Two-Way Operation*

Figure 314 illustrates the arrangements required graphically. It will be noted that this system provides for transmission in one direction only over each channel. If, as would ordinarily be the case, it is desired to transmit in both directions, three additional channels could be used with the sending and receiving channels for each message terminal, in telephone systems, brought together by means of bridge transformers. Or it is possible to establish a two-way circuit over a single carrier channel



**A. IMPRESSED TELEGRAPH CURRENT**

**B. UNMODULATED CARRIER CURRENT**

**C. CARRIER AFTER MODULATION BY A.**

*Fig. 316—Modulation in Telegraph Systems*

by inserting a bridge transformer between the terminal apparatus and the carrier line as well as between the apparatus and the message circuit line. These two possibilities are indicated by the drawings of Figure 315. Before reviewing the carrier frequencies used in practical systems or analyzing the circuit arrangements required for the operation of such systems, it is necessary that we examine briefly the principles of modulation and demodulation and of frequency selecting methods.

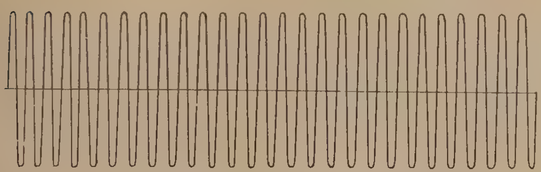
### 157. Modulation

Modulation has been defined as the process of impressing upon a carrier current, usually of a relatively high frequency, message currents of lower frequencies. The degree of difficulty involved in such a process depends upon the nature of the message current. For a telegraph current such as that shown in Figure 316-A, the method is very simple and consists merely in interrupting the supply of carrier frequency to the line during negative impulses of the telegraph signal and permitting it to flow during positive impulses. The result is to apply to the carrier line a series of "spurts" of current of the frequency of the particular carrier channel, as indicated in Figure 316-C.

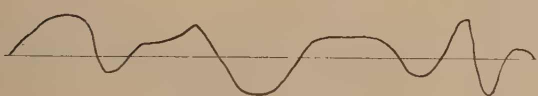
In telephony since the variations in voice current are much more complex than those of telegraph current, the process is somewhat more involved. It consists, however, of varying the amplitude of the carrier current to correspond to the variations of the voice currents. This is illustrated in Figure 317 where A is a representation of the unmodulated carrier current, B is a representative voice current and C is the modulated carrier current. It will be noted that the outline or "envelope" of the modulated current has the form of the voice current. This effect is not different in principle from the action of an ordinary telephone transmitter, where the direct current supplied by the local or central office battery is varied or modulated by the sound waves of the voice impinging on the transmitter button, so that the output current from the transmitter is

a varying direct current consisting of the initial unvarying battery current with the changing voice current superimposed upon it.

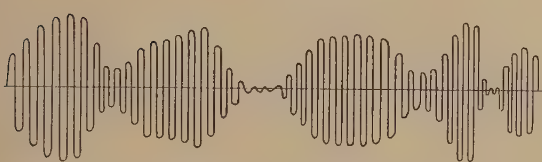
In the same way, the current of Figure 317-B could be obtained by connecting a transmitter in series with the carrier current generator, just as the battery is in series with the transmitter in the ordinary subset. The disadvantages of such a scheme will be apparent, however, and in practice the vacuum tube is used entirely for this purpose. In our study of this device in Chapter XVII, we found that by using suitable circuit arrangements and working on a straight line portion of the grid



A. UNMODULATED CARRIER CURRENT



B. VOICE CURRENT



C. CARRIER AFTER MODULATION BY B.

*Fig. 317—Modulation in Telephone Systems*

voltage-plate current characteristic of the tube, a small voltage impressed on the grid of the tube was capable of producing a substantial current in the plate circuit varying in exactly the same way as the voltage impressed on the grid; in other words, the tube acted as a powerful amplifier. If now we bias the tube so that we are no longer working on a straight line portion of the characteristic curve but on a definitely curved portion, the output current will no longer vary directly with the input voltage and while there will still be some amplification, it will no longer be constant but will depend on the value of the instantaneous input voltage. This distorting action of the tube is made use of in modulation.

In the simple circuit of Figure 318 let us assume that a voice voltage such as is represented by A is connected to the circuit through a transformer, together with the carrier voltage represented by B. For simplicity we have here assumed the voice voltage to be sinusoidal in form although this would not, of course, generally be the case. These two voltages being in series may be added together to give the voltage represented by C impressed on the grid of the tube. Now if the C battery or bias of the tube is given the value indicated by Figure 319, and the characteristic curve of the tube is as there shown, the impressed grid voltage will produce a plate current of the form shown in Figure 318-D,

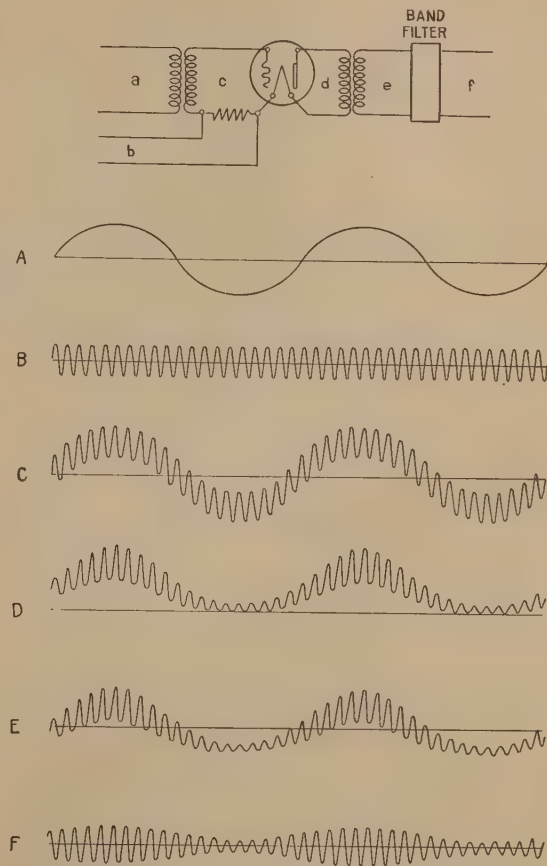



*Fig. 318—Currents in Modulator Circuit*

as may be seen by projecting each instantaneous value of the grid voltage curve of Figure 319 up to the grid voltage-plate current characteristic and over to form the plate current curve. After passing through the output transformer the current curve will be as pictured in Figure 318-E. This current curve may be analyzed by the method outlined in Article 3 of Appendix IV to determine its components. If this is done, it will be found that the principal frequencies present, in terms of the voice and carrier frequencies, are:

V — The voice current frequency
C — The carrier frequency

2V — Twice the voice frequency
2C — " " carrier "
C — V — The difference between the carrier and the voice frequencies
C + D — The sum of the carrier and voice frequencies.

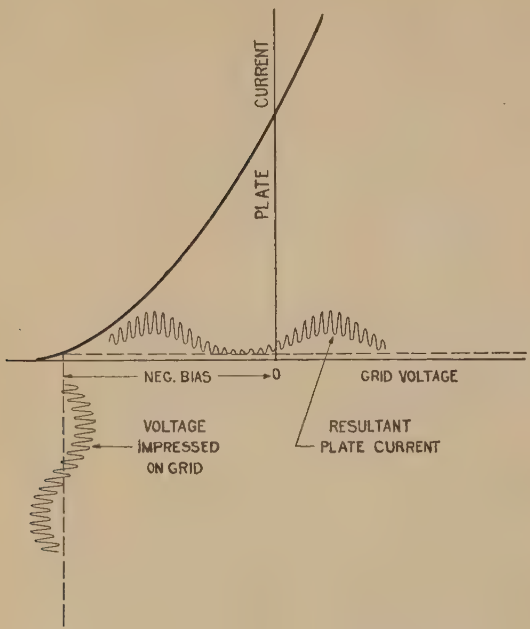



*Fig. 319—Action of Vacuum Tube in Modulation*

This result may also be reached by making the approximately correct assumption that the grid voltage-plate current curve, in the range used, is parabolic in form in which case the relationship between plate current and grid voltage may be written as a simple quadratic equation, thus:

$$i_b = K (E_b + \mu E_c + \mu e)^2 \quad \ldots\ldots\ldots\ldots (117)$$

where $K$ = a constant

$E_b$ = plate battery potential

$\mu$ = voltage amplification constant of tube

$E_c$ = "C" battery or biasing potential

$e$ = instantaneous alternating potential applied to grid

All of these values may be assumed to be held constant during the operation of the tube excepting $i_b$ and $e$. Expanding the equation, we have—

$$i_b = K [(E_b + \mu E_c)^2 + 2 (E_b + \mu E_c) \mu e + \mu^2 e^2]$$

or writing $a_1$ and $a_2$ for the coefficients of $e$ and $e^2$ respectively,

$$i_b = K (E_b + \mu E_c)^2 + a_1 e + a_2 e^2 \quad \ldots (118)$$

where $a_1 = 2 K\mu (E_b + \mu E_c)$

and $a_2 = K \mu^2$

Now the impressed voice and carrier currents represented in Figures 318-A and B are both sinusoidal in form and may be indicated mathematically by sine functions of time as $A \sin Vt$ and $B \sin Ct$ respectively, where $A$ and $B$ are constants. The applied input voltage, $e$, is then—

$$e = A \sin Vt + B \sin Ct \quad \ldots\ldots\ldots\ldots (119)$$

Substituting (119) in equation (118), we have for the output current—

$$i_b = K (E_b + \mu E_c)^2 + a_1 (A \sin Vt + B \sin Ct) + a_2 (A \sin Vt + B \sin Ct)^2$$

and, expanding—

$$i_b = K (E_b + \mu E_c)^2 + a_1 A \sin Vt + a_1 B \sin Ct + a_2 A^2 \sin^2 Vt + 2 a_2 AB \sin Ct \sin Vt + a_2 B^2 \sin^2 Ct. \quad \ldots\ldots\ldots\ldots (120)$$

Making use of the trigonometric relationships—

$$\sin^2\Theta = \tfrac{1}{2} - \tfrac{1}{2} \cos 2\Theta$$

and $\sin \Theta \sin \phi = \tfrac{1}{2} \cos (\Theta - \phi) - \tfrac{1}{2} \cos (\Theta + \phi)$,

we may expand further to obtain—

$$i_b = K (E_b + \mu E_c)^2 + a_1 A \sin Vt + a_1 B \sin Ct + \tfrac{1}{2} a_2 A^2 - \tfrac{1}{2} a_2 A^2 \cos 2 Vt + a_2 AB \cos (C - V)t - a_2 AB \cos (C + V)t + \tfrac{1}{2} a_2 B^2 - \tfrac{1}{2} a_2 B^2 \cos 2 Ct$$

$$= K (E_b + \mu E_c)^2 + \tfrac{1}{2} a_2 (A^2 + B^2) + a_1 A \sin Vt + a_1 B \sin Ct - \tfrac{1}{2} a_2 A^2 \cos 2 Vt - \tfrac{1}{2} a_2 B^2 \cos 2 Ct + a_2 AB \cos (C - V) t - a_2 AB \cos (C + V)t \quad \ldots\ldots\ldots\ldots (121)$$

An analysis of this equation shows the first and second terms to be constants representing direct current which, of course, will not appear on the line side of the transformer. The third and fourth terms are merely amplified currents of voice and carrier frequency respectively; the fifth and sixth are sinusoidal currents of double these frequencies; while the last two represent respectively the difference and the sum of carrier and voice frequencies. If, therefore, the voice and carrier frequencies applied to the grid had been, for example, 1,000 and 10,000 cycles respectively, the output of the circuit would have contained currents of frequencies 1,000, 10,000, 2,000, 20,000, 9,000 and 11,000 cycles. Practically, of course, applied voice currents would contain several frequencies which might have any values between, say, 200 and 2,500 cycles, and the output current would vary accordingly. Thus, the output frequency indicated in equation (121) as the sum of the voice and carrier frequencies, might occupy any value in the band of frequencies between (C + 200) and (C + 2500).

These sum and difference frequencies are called the upper and lower modulation components, respectively, or, more commonly, the **upper and lower side-bands, and either one of them is by itself cap-**

able of carrying the voice current to the receiving end of the circuit. In practice, accordingly, it is customary to suppress by means of filters or otherwise, all of the frequencies in the output of the modulators except one side-band, and in some cases the carrier itself, for transmission over the line, although our theoretical diagrams of Figures 314 and 315 showed the output of the modulators connected directly to the line.

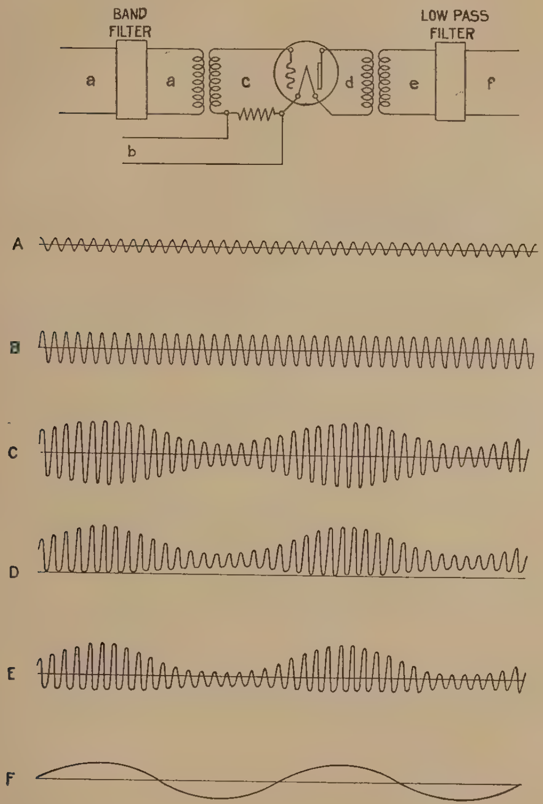



*Fig. 320—Currents in Demodulator Circuit*

In Figure 318-F the band filter has blocked all frequencies except the carrier and the lower side-band. It is obviously desirable also to so arrange the modulator circuit that the side-band current to be transmitted over the line has the largest possible value, and the currents that will not be needed have small values, thus making feasible the utilization of the greatest possible part of the modulator tube's output energy. This result can be to a degree achieved by properly adjusting the values of the constants $a_1$, $a_2$, A and B in equation (121). Referring to this it will be noted that if $a_1$ is made very small, the voice and carrier frequencies may be practically eliminated from the output. This may be accomplished by giving $E_c$ a large negative value, in which case the factor, $(E_b + \mu E_c)$, in the expression for $a_1$ ($a_1 = 2K\mu\,[E_b + \mu E_c]$) may be made to approach zero, reducing $a_1$ correspondingly. In case the carrier itself is to be transmitted, the reduction of $a_1$ in the carrier term, $a_1$ B sin Ct, must be compensated for by a corresponding increase in the value of B. But this constant also occurs in the side-band term so that an increase in its value is advantageous for both of the frequencies to be transmitted. This means simply that in systems where the carrier is transmitted, the carrier voltage applied at the modulator should have a large value as compared with the voice voltage.

## 158. Demodulation

If only a side-band current is transmitted over the line as indicated by Figure 320-A instead of both side-band and carrier, it is necessary to supply to the demodulator from a separate source, current of the carrier frequency. This current must, of course, be of exactly the same frequency as the carrier supplied to the modulator of the same channel.

The action of the demodulator is identical in principle with that of the modulator, as may be seen from an examination of Figure 320. The locally applied carrier B adds to the incoming side-band A, which in this case is supposed to be carrying a voice current of a single frequency, to give the net voltage C impressed on the grid. (Note that the resultant current is the same as that shown in Figure 318-F). Thus we have impressed (C + V) and C. If we substitute these values for e in equation (118) and expand, we will find that the resultant output currents are—

C—The carrier frequency.

(C + V)—The impressed side-band frequency.

2C—Twice the carrier frequency.

2 (C + V)—Twice the impressed side-band frequency.

(C + V) + C = 2C + V—The sum of carrier and side-band.

(C + V) —C = V—The **difference** of carrier and side-band, which is the **voice frequency.**

All of these currents are present in Figure 320-D and Figures 320-E and F represent respectively the complex current on the drop side of the output transformer and finally the voice current itself after the higher frequencies have been eliminated by means of a **low pass** filter.

In telegraph systems the process of demodulation is relatively simple, as in the corresponding modulation. As noted in Article 157 the modulated current transmitted over the line consists of a series of "spurts" of alternating current of the single frequency of the carrier. This incoming current, represented by Figure 321-A, after being selected by the proper filter, is led to a vacuum tube, the grid of which is so strongly biased that it acts as a rectifier. The resultant output is an unidirectional varying current, as shown in Figure 321-B. An analysis of

this current would show it to consist essentially of two components, a direct current and a superimposed alternating current of the carrier frequency. The alternating current is filtered out by a simple condenser arrangement, leaving only a series of pulses of direct current corresponding in duration to those applied at the sending end of the circuit, as illustrated by Figure 321-C. These direct current impulses are then used to operate a relay, the contacts of which control the battery connections to the usual telegraph repeating apparatus and establish the operating current of Figure 321-D.

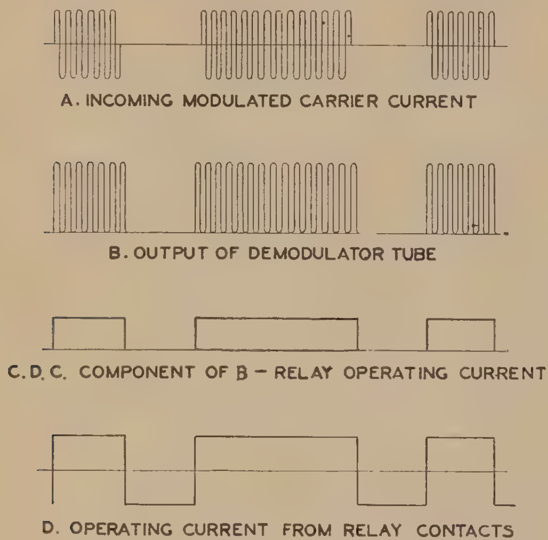



*Fig. 321—Demodulation in Telegraph Systems*

### 159. Selecting Circuits

We have noted the necessity for selecting circuits or electrical filters at various points in every carrier system. Thus we have seen the need for filters (a) between the carrier line and the output of the modulator circuit to suppress those frequency products of modulation the transmission of which over the line would serve no useful purpose; (b) between the carrier line and the input to the demodulator circuit to separate the different channels and to select for each demodulator circuit the proper modulated carrier current; and (c) between the output of the demodulator and the circuit terminal to suppress all other products of demodulation except the desired message current. In addition to these when, as is most commonly the case, the carrier system is superimposed on an ordinary telephone circuit, it is necessary to use filters to separate the normal voice current from the carrier currents as a group, at the circuit terminals. It may also be necessary to so separate the currents at intermediate points on circuits where it is expedient to install repeaters or amplifiers in the voice or carrier circuits or in both, or at points where the voice or carrier drops, or the carrier is transferred from one circuit to another. Further, in systems in which transmission in the two directions is effected by the use of carriers of different frequencies, the currents transmitting in opposite directions are separated as a group at repeater points and, in more recently designed systems, at the terminals also by means of "directional" filters. The schematic layout of such a system is shown by Figure 322 where, it will be noted, amplifiers common to the receiving and transmitting sides of all channels are also indicated. Such amplifiers are used to maintain the carrier current at the proper energy levels and are required in all carrier systems although in some systems amplifiers individual to each channel are used instead of as shown in Figure 322.

The low pass and high pass filters shown connected across, and in series with the line, are the type described in Article 139. The former permits the passage of currents of frequencies within the

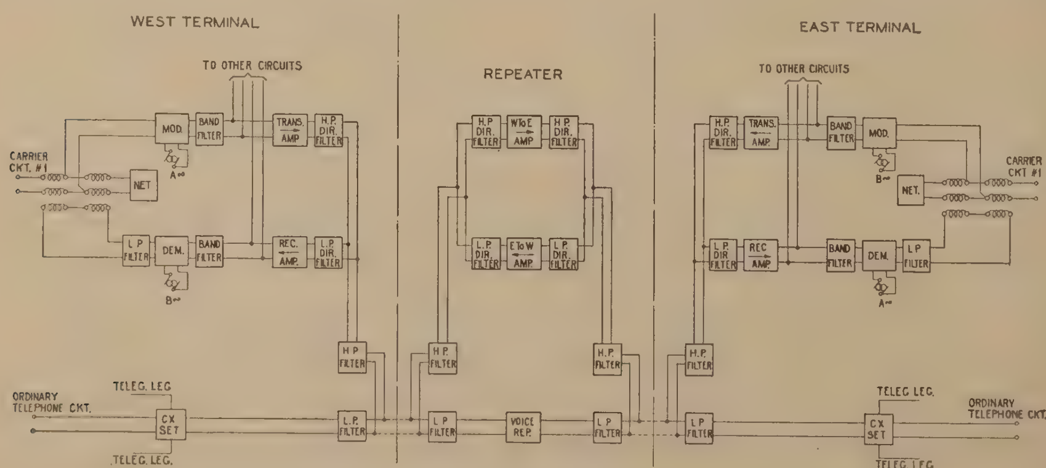



*Fig. 322—Typical Carrier System Layout Showing Filter Arrangements*

normal voice range, from zero to about 3,000 cycles, and blocks all higher frequencies, while the latter stops the voice frequencies and passes all higher frequencies. The directional filters are also high pass and low pass filters, but have cut-off points midway of the carrier range so that one passes carrier currents below a certain value, in which range are included all of the carriers transmitting in one direction, while the other blocks these and passes only frequencies above this value, which includes all of the currents transmitting in the other direction. The low pass filter connected to the output of the demodulator is identical with the low pass filter in series with the line, and likewise passes voice current only.

In telegraph systems the selecting circuits need only be simple resonant circuits of the type described in Article 98, since only the single frequency of the carrier itself is used in transmitting telegraph messages. In telephone systems, on the other hand, it is necessary to transmit over each channel a band of frequencies consisting of either the upper or lower side-band and, in some cases, including the carrier frequency itself. The selecting circuits must therefore be designed to permit the passage of a band of frequencies 2,000 or more cycles in width and to suppress all others. For this purpose the band filters described in Article 139 are used.

## 160. Types of Carrier Systems

Thus far our discussion has been for the most part confined to the fundamental theory and general aspects of carrier systems. Now, without making a detailed study of any particular types of systems, we may note the different standard systems in use and compare their chief points of similarity and difference. Although telephone and telegraph carrier systems are alike in all essential principles, they are ordinarily treated separately because of the basic differences in the two types of services.

There are in use two types of carrier telegraph systems. The first, from the viewpoint of length of service, is the so-called "high frequency" system in which as many as ten telegraph message channels may be superimposed on an open wire telephone circuit, which may also be composited for ordinary grounded telegraph. In this system twenty carrier frequencies are used, ranging in value from 3,333 cycles to 10,000 cycles. The lower ten frequencies are used for transmission in one direction and the higher ten for transmission in the

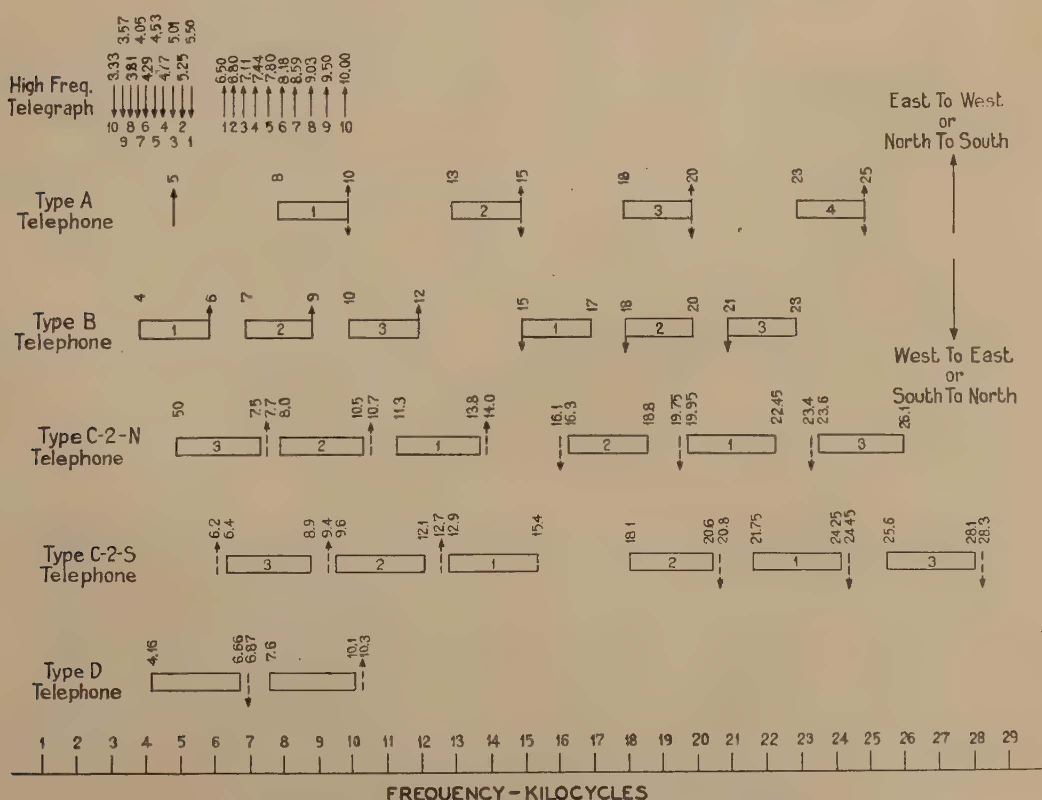



*Fig 323—Frequency Allocations for Carrier Systems*

opposite direction. The exact frequency allocation for each channel may be found by referring to Figure 323. With the carrier frequencies so grouped for transmission in the two directions, separation at repeater points is secured by directional filters, one of which passes only frequencies below 6,000 cycles and the other only frequencies above that value. Directional filters are also used in the same way for separating the transmitting and receiving channels at the circuit terminals, although bridge transformers were once generally used for this purpose. The essential elements of such a system are indicated by Figure 324, and Figure 142 of Chapter XII shows the terminal circuits in some detail.

The second type of telegraph system is the "voice frequency" system, so called because the carrier frequencies used are within the band of ordinary voice frequencies. The principle of this system is not essentially different from that of the high frequency system, but due to the lower frequencies used there is considerable variation in the details of the apparatus. The system is installed exclusively on 4-wire cable circuits and since its operation would interfere with ordinary telephone transmission it cannot be superimposed on a telephone circuit. It does not, however, interfere with the circuits use for standard metallic telegraph message circuits. As a 4-wire circuit is employed there is no problem in separating the transmitting and receiving channels and the same carrier frequency can be used for transmission in the two directions. Also, since all frequencies are within the normal voice band, the transmission characteristics of the circuit and its included telephone repeaters need be no different from those of the standard 4-wire telephone circuit. Figure 325 shows the general layout of the system and the carrier frequencies used for the various channels. It will be noted that these are multiples or harmonics of a fundamental frequency of 85 cycles, and that there is a separation of 170 cycles between adjacent channels. The carrier sending and receiving apparatus is similar to that of the high frequency system, "spurts" of the carrier current being sent over the line as the transmitting amplifier is shorted out by the telegraph impulses, and a rectifying device at the receiving end converting the "spurts" of carrier back again to ordinary D.C. telegraph signals.

One of the chief differences between the two types of telegraph systems lies in the method of generating the carrier frequencies. In the high frequency system, as in all telephone systems, vacuum tube oscillators perform this function. In the voice frequency system, it is possible because of the relatively low values of the carrier frequencies, to employ a specially designed small rotating machine of the inductor type, one of which is capable of generating all of the carrier frequencies for several systems. The machine is held to a constant speed by means of a mechanical governor, associated with which is a vacuum tube indicating device, so that the carrier frequencies will maintain the values for which the selecting circuits are designed.

Now, turning our attention to telephone systems, there are four types in which we are interested. The first of these, type A, is now practically obsolete, but as the first developed carrier system, it may be of interest to review very briefly its principal features. The system as originally designed was a balanced one, i.e., the same carrier frequency was

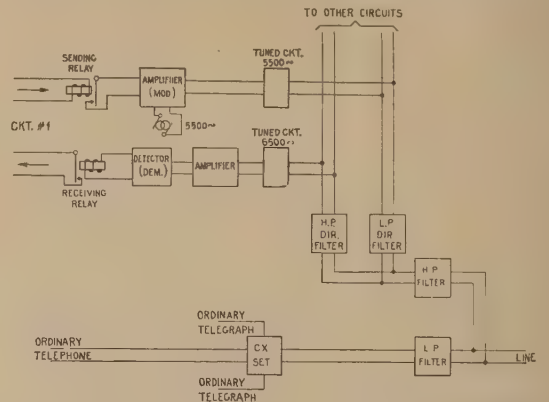



*Fig. 324—High Frequency Carrier Telegraph Terminal*

used for transmission in the two directions on each channel. With this arrangement four telephone circuits were obtained, employing the frequency band for each channel indicated in Figure 323. This required the use of bridge transformers and networks for balancing the line through the entire carrier range at both terminals and at any repeater points. The extreme difficulty of securing good balance between a line and network through a range of frequencies running up to 25,000 cycles was the chief reason for the abandonment of this system in its original form. Where now in service, balance problems are eliminated either by using a separate pair of wires for transmitting and receiving or by employing two of the channels for transmitting and the other two for receiving, thus reducing the total number of carrier circuits obtained from four to two. A schematic layout of a type A system terminal is shown in Figure 326.

The carrier frequency itself is suppressed in the modulator, only the 2,000-cycle lower side-band being transmitted over the line for each channel. The carrier frequencies are all harmonics of a single frequency, 5,000 cycles, and are all obtained from one master 5,000-cycle vacuum tube oscillator. At the terminal where this oscillator is located, its output is sent through a "harmonic producer", which is simply a vacuum tube amplifier so overloaded that its output is badly distorted and contains a large group of frequencies including the impressed 5,000-cycle frequency and all of its harmonics. As shown by the diagram, the second harmonic, or 10,000-cycle current, is selected by a tuned circuit, amplified and lead to the modulator and demodulator of the first carrier channel. The 15,000-cycle third harmonic is selected for the

second channel and so on. In addition, the fundamental frequency of 5,000-cycles is amplified and sent over the line to the distant end where it is selected by a tuned circuit, amplified and fed to a "harmonic reproducer", which is identical to the harmonic producer and contains in its output the multiple frequencies of the fundamental needed for the operation of the demodulators and modulators at that end. This control channel insures that the carrier frequencies used at the two terminals are absolutely identical in value, since they are derived from the same source. A casual inspection of Figure 326 will show, however, that the type A system requires the use of a great deal of apparatus. The need for effecting economy by simplification, together with the balance difficulties inherent in this system, led to the development of the type B system.

by transmitting the carrier frequency over the line along with one side band. This does away with the necessity for furnishing current of the proper carrier frequency to the demodulators from a separate source, but, as will be noted later, makes the problem of securing satisfactory transmission over the line somewhat more severe.

In the type A system, signaling is accomplished by modulating the 135-cycle ringing current on the carrier exactly as if it were a voice current. After demodulation at the receiving terminal, it operates the ordinary composite ringer circuit, transmitting the signal to the switchboard drop. In the type B system, signaling is effected by interrupting the flow of the carrier current over the circuit by short-circuiting the oscillator. The resultant stopping of the normal flow of current to the input of a rectifier

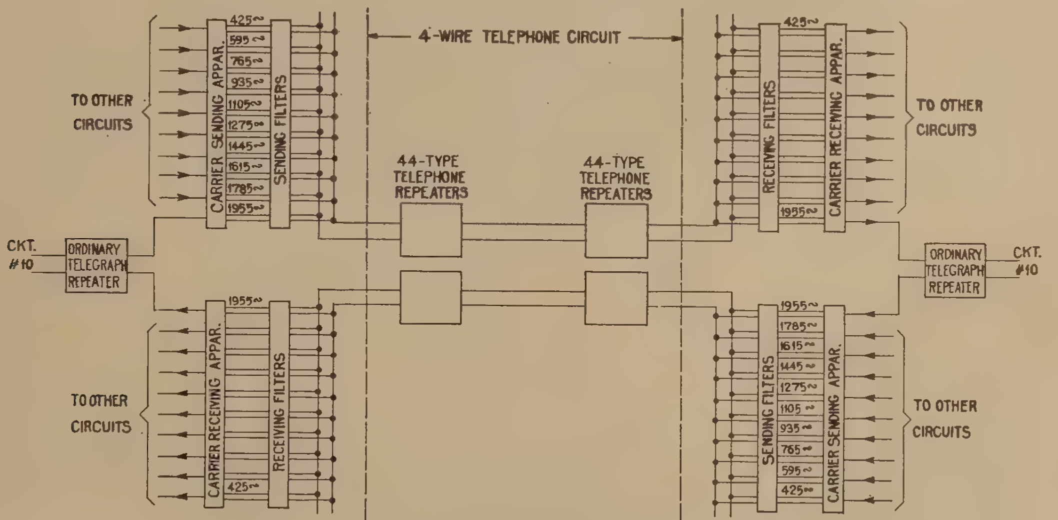



*Fig 325—Voice Frequency Carrier Telegraph System*

The problem of balance is obviated in the type B system by using separate carrier frequencies for transmission in the two directions as indicated by Figure 323. This involves, however, the sacrifice of one carrier circuit as compared with the type A, reducing the total number of superimposed telephone circuits obtained to three. The band of frequencies transmitted over each channel is of the same width as in the type A system, namely, 2,000 cycles, but the separation between channels transmitting in the same direction is reduced to 1,000 cycles. The carrier frequencies are spaced 3,000 cycles apart, beginning at 6,000 cycles, but since the lower side-band is used for the three channels transmitting in one direction, and the upper side band for the three channels transmitting in the opposite direction, the separation between the two directional groups is 3,000 cycles. The rather complicated system of generating the carrier current employed in the type A system is eliminated

tube, bridged across the receiving circuit at the output of the demodulator amplifier, reduces the plate current of the rectifier tube and allows a relay to release, which transmits the signal to the circuit drop. In addition to its use in connection with signaling, the bridged rectifier arrangement also provides a mean of keeping a check on the transmission efficiency of the circuit. A D.C. meter inserted in its plate circuit gives effectively a measure of the received carrier current and any observed change in its value may be compensated for by a corresponding adjustment of the terminal amplifier. Figure 327 gives a schematic of the arrangement of the terminal circuit.

The type C system utilizes the best features of both the A and B systems and avoids the major drawbacks of both. It is a carrier suppression system and it uses separate channels for transmission in each direction. The schematic layout of

the terminal circuit may be seen by referring to Figure 322. Individual oscillators of an improved type are used for generating the carrier current supplied to the modulators and demodulators. These are of such stability that special methods of maintaining frequency synchronization between the two terminals of a channel, such as the control channel of the type A system, can be dispensed with entirely. Further simplification of apparatus is obtained by the use of a single amplifier common to all channels transmitting in each direction, instead of an amplifier associated with each demodu-

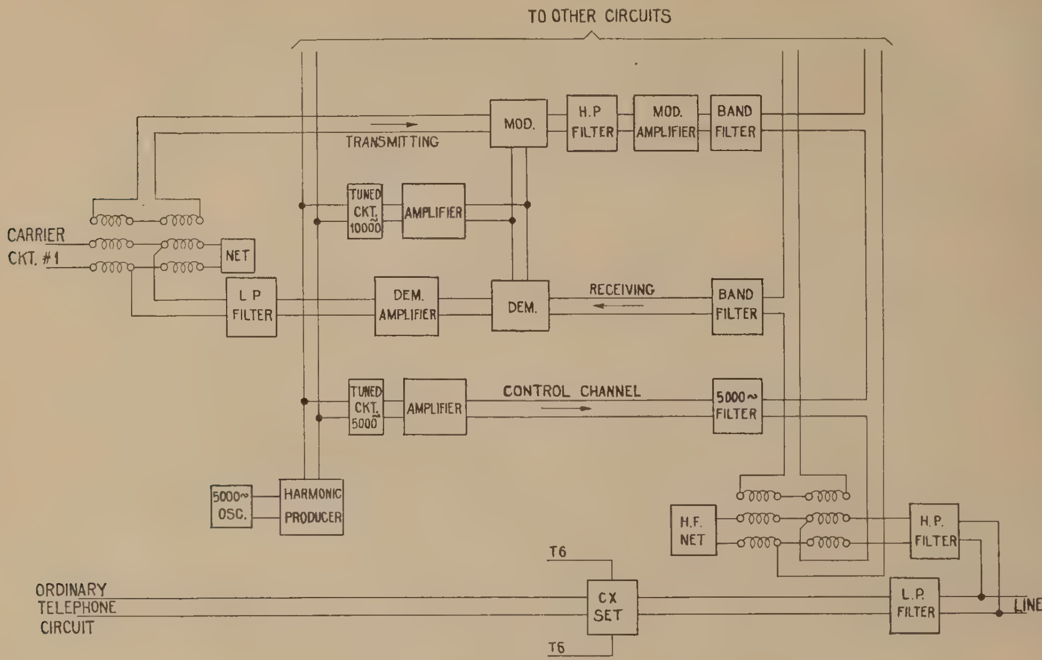



*Fig. 326—Type A Carrier Telephone Circuit Terminal*

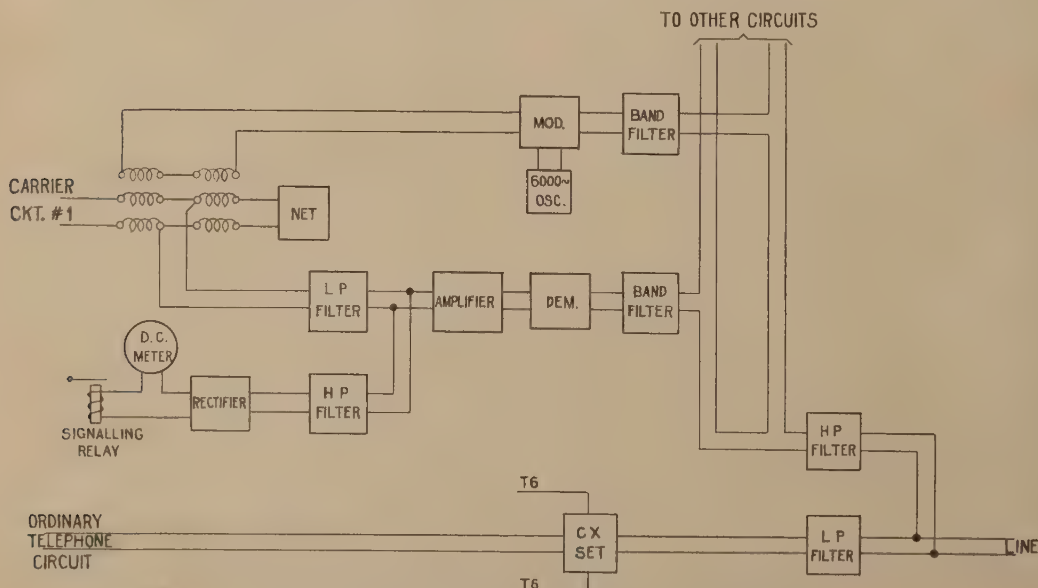



*Fig. 327—Type B Carrier Telephone Circuit Terminal*

# CARRIER CURRENT SYSTEMS

*Above left*—Carrier telephone repeater equipment.
*Above right*—High-frequency carrier telegraph terminal.
*Right*—Type "C" carrier telephone terminal.
*Below*—Typical installation of voice-frequency carrier telegraph terminal equipment.

lator as in the type B system, or with each modulator and demodulator as in the type A system. One thousand-cycle signaling is employed, the ringing current being transmitted over the system in exactly the same way as are voice currents.

In order to avoid crosstalk where two or more carrier systems are operated on the same pole line, there are two standard channel frequency allocations. Referring to Figure 323, the first, or C-2-N system, extends from 5,000 cycles to 26,100 cycles, with the lower side-band used in the three lower frequency channels transmitting in one direction, and the upper side-band used in the three higher frequency channels transmitting in the opposite direction. The C-2-S, or "staggered" system, employs the frequency range from 6,200 cycles to 28,300 cycles with upper side-band operation in the lower frequency group and lower side-band operation in the higher frequency group. The advantages of this arrangement will be evident from a study of the Figure, where it will be noted that the most important range of frequencies in each side-band for one system, is opposite a blank space in the other system. It may also be noted that the C-2-N system is staggered in much the same way with respect to the type B system, thus permitting satisfactory operation of these two types of systems on the same open wire line. The employment of an improved type of band filter in the C system permits closer spacing of the channels and, at the same time, the transmission of a 2500-cycle band of frequencies instead of the 2,000-cycle band of the older systems, thus improving the quality of transmission.

The feature of the type B system whereby it is possible to observe the transmission efficiency of the system while it is in operation by measuring the rectified carrier current, may be retained in the C system by the use of "pilot channels". This involves putting on the line at each terminal a single frequency selected so that it will not interfere with the voice channels, and will still be representative of the carrier range, and measuring the received currents by means of rectifiers and D.C. meters. Frequencies lying in the interval between the middle and one of the adjacent channels in each of the directional groups are selected for the pilot channels. The pilot channel current is rectified at the terminals and at all repeater points. By means of alarm circuits associated with the indicating meters, any appreciable variation of energy levels at any point in the circuit makes itself known and is compensated for by adjustment of the amplifier gain.

There is one other type of telephone system used to a very limited extent in the Long Lines Department, known as Type D. It provides only one carrier circuit employing carrier frequencies of 6870 cycles and 10300 cycles for transmission in the two directions. Lower side-band operation with transmitted band widths of 2500 cycles is used in both channels. The system is designed primarily for application on comparatively short circuits, 100 to 150 miles in length.

## 161. Carrier Transmission

We have already noted that the problem of transmitting over long distances the relatively low frequency currents used in the voice frequency carrier telegraph system, does not differ in essentials from that involved in the ordinary 4-wire telephone circuit. For the high frequency telegraph system and for all carrier telephone systems, however, the transmission problem is more severe. The high frequency carrier currents, of course, behave in accordance with the same general laws of transmission as we have studied in connection with ordinary voice transmission. But, due to the increase of effective resistance of the line wires and the decrease in their effective insulation as the frequency increases, the attenuation increases very rapidly as shown by the curves of Figure 328. Furthermore, as would be expected, the increased importance of the leakage factor as the frequency increases makes for much greater variation of the attenuation with changing weather conditions than at voice frequencies. There is now being used, on many carrier circuits a special type of glass insulator having a lower dielectric loss than the standard type, which serves to alleviate the difficulty to some extent, reducing both the unit attenuation and the amount of variation with weather changes.

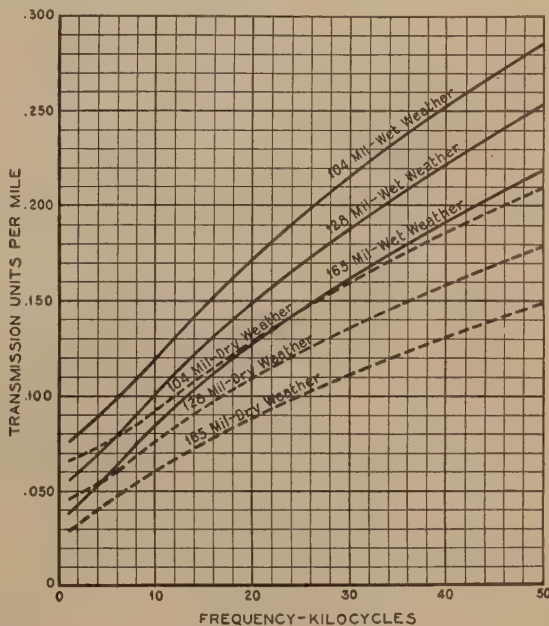



*Fig. 328—Attenuation of Non-Loaded Open Wire Circuits at Carrier Frequencies*

The curves of Figure 328 apply as indicated, to non-loaded open wire circuits. In loaded aerial bare wire circuits, the increase in attenuation is very much more rapid above the cut-off point of the loading which, as we have learned, occurs near the higher end of the normal voice band. The same

applies to all standard "voice loaded" cable circuits, so that the application of any but voice frequency carrier systems to either type of circuit is out of the question in practice. Unfortunately, however, practically every non-loaded open wire circuit includes some lengths of toll entrance or intermediate cable in its make-up. Left non-loaded, these cable lengths would attenuate high frequency carrier currents less than if loaded with a standard voice frequency loading system but would nevertheless introduce extremely large losses as compared with equal lengths of the non-loaded open wire. The difficulty is overcome by specially loading the sections of toll entrance or other cable included in circuits to which carrier systems are to be applied, in such a way that the cut-off frequency is higher than the highest carrier frequency. This requires, as we would expect from our study of the theory of loading in Chapter XXI, the employment of very low inductance coils spaced at short intervals. In practice, coils having an inductance of 4.1 or 4.8 mil henries and connected into the circuit at intervals of 929 feet are used. In addition to reducing attenuation, the loading is so designed as to eliminate reflection losses by matching the impedance of the cable to that of the non-loaded open wire connected to it.

miles is necessary. Since the carrier repeater must handle substantially greater quantities of energy than the standard voice repeater, it is radically different in design, although not in principle. As illustrated in Figure 329, it is a two-stage repeater employing two tubes, operating "push-pull" in the first stage and four tubes in two parallel "push-pull" groups in the second stage. The latter are of the "O" or 104 type, permitting a possible maximum power output for the amplifier of more than .5 watt as compared with about .05 watt for the "L" tube of the 22-A-1 repeater. As has been previously mentioned, separation between the currents being transmitted in the two directions is effected in all except the type A telephone system, by means of directional filters rather than by the use of bridge transformers.

The gain-frequency characteristics of the repeaters are adjusted to compensate for the increasing attenuation of the line with frequency by means of **equalizers.** Earlier types of repeaters were equipped with three separate equalizers, any one of which could be connected in the circuit by operation of a key. One of these was for use when the repeater was operating in a telephone system, one when it was used in a telegraph system and the third for testing purposes. Representative gain characteristics for such a repeater with each of the three equalizers connected in its circuit are shown in Figure 330. A later type is used exclusively with type C telephone systems and the telegraph equalizer is accordingly eliminated. Except for this feature, however, and a change in mechanical assembly of parts, this repeater does not differ essentially from the older model.

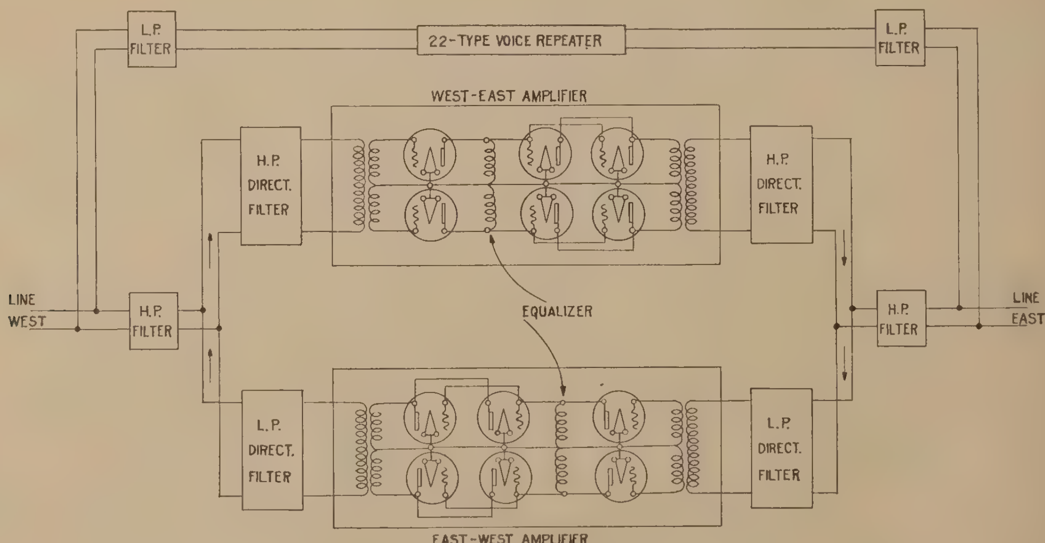


*Fig. 329 Carrier Repeater*

While it is practicable to apply considerably larger amounts of energy to the line in carrier systems than to the ordinary telephone line (up to 25 TU above zero level in the type C system), the high line attenuation necessitates the use of intermediate repeaters on long circuits at fairly short intervals. On high grade 165 circuits, an average spacing between repeaters of not more than about 180 miles is required for type C systems, and if 104 circuits are used a spacing of approximately 140

The advantage of staggering the frequency allocations for the several channels when two or more carrier systems are operated on the same line was brought out in the preceding Article. Usually, however, this procedure alone is not sufficient to reduce inter-system crosstalk and absorption of energy to the allowable maximum. It is ordinarily necessary in addition, that the line wires be specially transposed according to a somewhat more elaborate system than is required for the satisfactory operation of voice frequency circuits alone. Carrier circuits are immune to much of the noise induction affecting voice circuits, due to the higher frequencies of transmission. They are more subject to interference from atmospheric disturbances ("static") and high powered radio transmitting stations. By maintaining the carrier energy levels at high values in exposed sections of the line, however, the effect of the induced noise currents can usually be largely nullified.

Perhaps the most difficult problem in the operation of carrier systems is that caused by the abnormally wide variation in attenuation characteristics of the lines due to changing weather conditions. This is particularly serious in the type B telephone system where both the carrier itself and a side-band are transmitted. As we learned in our study of modulation and demodulation, the value of the final received voice current varies as the product of these two high frequency currents and since both will be attenuated in passing over the line, any change in the amount of attenuation caused by the line, will result in twice as great an effect on the overall voice transmission as would be caused by the same change in a system transmitting only one side band.

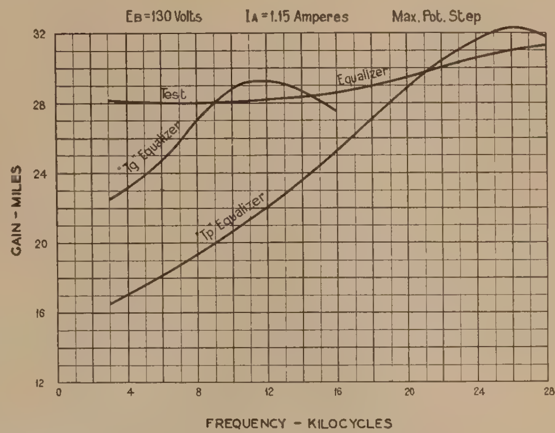



*Fig. 330—Gain-Frequency Characteristics of Carrier Repeater with Various Equalizers*

This difficulty may be overcome by making such frequent adjustments to the gains of the terminal amplifiers, and if necessary the intermediate repeaters also, as to hold the transmission levels at approximately constant values. When this is done, well designed carrier systems will provide telegraph circuits appreciably better than the ordinary grounded circuit and telephone circuits at least as good as the voice circuits obtained from standard high grade loaded open wire facilities.

# APPENDIX I

## PHYSICAL QUANTITIES AND THEIR UNITS OF MEASUREMENT

### 1. Mechanical Quantities

In addition to the general physical quantities, **force, work** and **energy** the essential ones belonging to the mechanical group are **time, length, area, volume, mass, density, speed, acceleration,** and **power.** The combined group consists of two classes, viz. (a) those that are fundamental, and (b) those that may be defined from their relations to the fundamental ones.

In dealing with any one physical quantity we need first to know its definition or exact nature and next the method whereby it may be measured. Its measurement will always require a comparison with some unit which is either a fixed standard or may be derived from some fixed standard or standards. In addition to this it may sometimes require the fixing of a positive or negative sign to the numerical size of the quantity.

### 2. The Three Fundamental Units

There are three units that are fundamental to all mechanical measurements. We may either use these directly to measure any quantity in which we are interested or to derive other units with which the quantity may be measured. These fundamental units, which we must preserve as standards and which must be remembered at all times because they cannot be produced mathematically, are **the unit of time, the unit of length and the unit of mass.**

We daily express periods of time by comparison with familiar units such as second, minute, hour, day and year and have vivid conceptions of their size or greatness, for example: 10 minutes, 2 hours, 3 years, etc. We likewise express distances by comparing them with simple units of length such as inch, foot, yard, mile, etc.

Though the fundamental units of time and length are too familiar to require discussion, the conception of the third fundamental unit or **the unit of mass** is easily confused with the conception of force, and the every day term **weight** may be wrongly taken to mean **mass.**

Mass is defined as amount of matter. There is a piece of platinum carefully preserved in the Standards Office at Westminster which is called the "Imperial Avoirdupois Pound", and this is our standard unit of mass. There is no direct method of comparing the mass of bodies of other material with this piece of platinum and an indirect method must be used. The earth exerts a force of attraction called **gravity** on the mass of all bodies and in practice we merely compare these forces (or **weights**) rather than make a direct comparison of masses. But what are being compared are in reality forces and not amounts of matter.

From the same units with which we express distances, that is, from the units of length, we may derive mathematically units for area or volume. For area, such units are the square inch, the square foot, the square mile, etc. and for volume they are the cubic inch, cubic foot, cubic yard, etc.

### 3. Density and Specific Gravity

**Density** is defined as the mass per unit volume of a substance. To measure it we employ the unit of volume (length x length x length) and the unit of mass, i.e., mass divided by volume. In practice we seldom use density in the absolute sense but use instead **specific gravity.** The specific gravity of any material is the ratio of the weight of a given volume of that material to the weight of an equal volume of water. For example, the specific gravity of cast iron, a cubic foot of which weighs approximately 500 lbs., is 7.7 since a cubic foot of water weighs approximately 62-½ lbs. Likewise the specific gravity of the electrolyte (diluted sulphuric acid) which is ordinarily used in storage batteries is about 1.200, which means that any unit of its volume will weigh 1.2 times as much as the same volume of water.

### 4. Velocity or Speed

We may express **speed** or **velocity** as the time rate of traveling **distance.** If any body in motion, such as a train, continues its motion without change for one unit of time, such as the hour, the distance is a quantitative measure of its speed. For example, a train's speed may be thirty miles per hour which means if it keeps moving for one hour with the same speed as at the instant observed, it will cover a distance of thirty miles. This does not mean, however, that the train will keep moving for one hour or that it will eventually move the distance of thirty miles; it merely means that if the conditions under which the train is moving at the instant observed are unchanged during a one hour period the train will traverse a distance of thirty miles.

### 5. Acceleration

If the train at any time should either acquire more speed or "slow down" it would be accelerated. **Acceleration** is defined as the time rate of changing speed. A train is positively accelerated when getting up to speed and negatively accelerated when slowing down. This quantity is an ideal example of a measurement requiring more than a mere numerical comparison. If in one minute's time the train should **increase** its speed one mile per minute, it would have one unit's **positive** acceleration or an acceleration of **plus** one mile — per minute — per minute; if in the same length of time it **decreased**

its speed one mile per minute, it would have **negative** acceleration of one mile — per minute — per minute.

### 6. Force

Mass, such as the piece of platinum already mentioned, is drawn toward the center of the earth by the force of gravity. If it were free to fall, the force of gravity would give to it an acceleration of about 32 feet — per second — per second; that is, at the end of the first second from the time it started to fall it would have a velocity of 32 feet per second and at the end of the next second a velocity of 64 feet per second, etc. That influence which tends to set any body in motion or to change the direction or speed of any body already in motion is called **force.** The **unit** of **force** is that force which the influence of gravity exerts on the standard pound of mass when at sea level. It is called the **pound of force.**

When the forces acting upon a body in any one direction are equal to those acting in the opposite direction, the body is in equilibrium or at rest. When these forces become unbalanced, the body is set in motion and work is performed.

### 7. Work

**Work** is done when a force moves a body **in the direction of the force.** It is measured by the product of the force and the distance through which it acts. If a pound of force acts upon a body through a distance of one foot, one **foot-pound** of work is performed. If a six pound hammer is raised from the floor to a bench three feet in height, six times three or eighteen foot-pounds of work is performed. If the vertical distance between the two floors of a building is 12 feet and a man weighing 150 pounds ascends from one floor to another he performs 12 x 150 or 1800 foot pounds of work. Here it should be noted that the force acts through the vertical distance only and not through any horizontal distance he may travel while ascending flights of stairs. The distance must be measured parallel to the direction of the force.

Work in its scientific sense is measured by the result and not by effort or exertion. A man may attempt to move a weight until he is fatigued, but he performs no **mechanical work** unless he succeeds in elevating the weight against the force of gravity, changing its position in a given plane against the friction and inertia tending to hold it at rest, or overcoming any other resisting forces that may be acting upon it.

### 8. Power

In the same sense that speed is the time **rate** of traversing distance, **power** is the time **rate** of **doing work.** Its unit of measurement, therefore, not only requires the fundamental units of foot and pound for its derivation but must include time also. If a machine is capable of performing 33000 foot-pounds of work, we have no conception of the size of the machine. It may be a small machine capable of performing this amount of work in fifteen days or a large machine capable of performing the work in three seconds, but a machine that can perform **33000** foot-pounds of **work in one minute** is rated at **one horse power.**

### 9. Energy

**Energy is ability to do work or is stored work** and may therefore be expressed in the same units as work. A suspended weight or a fly wheel in motion are said to have stored mechanical energy by virtue of their ability to perform useful work.

Energy also exists in forms other than mechanical. A strong acid may have the ability to dissolve metals; a solution may have the ability to generate an electrical current when in contact with two dissimilar metals. Food, when digested, permits man to perform useful tasks. These are examples of ability to perform work, but the **energy** is in a **chemical** and not a **mechanical state.**

Another very common form of chemical energy is that of coal which when burned gives off large quantities of heat. Heat is within itself a form of energy and may be made to perform work. It may be applied to a boiler in such manner as to generate steam under pressure and the steam may be used to operate an engine or turbine. The amount of **heat** required to raise the temperature of one pound of water one degree Fahrenheit is the **British Thermal Unit.**

The following have approximately equal energy values, viz.: 10,000,000 foot-pounds:

1. One pound of coal.
2. One day's supply of food for adult man of average muscular vigor.
3. Type 11-E 24-volt Chloride Accumulator fully charged.
4. Amount of water in average railroad water tank when elevated from ground level.

Energy may be converted from one form to another but **can never be produced or destroyed.** This does not mean, however, that one pound of coal could be made to pump sufficient water to fill the railroad water tank mentioned in the foregoing. The best known devices for converting heat or chemical energy into mechanical energy are very inefficient and only a small part of the coal's energy value can be made to produce useful work, the greater portion being lost by heat radiation or conduction rather than utilized by conversion.

### 10. The Metric System of Measurements

The system of measurements used by all civilized countries except Great Britain and the United States is called the **metric system.** It is based upon multiples of ten or upon the decimal plan, in a

manner similar to that of our money system in this country. On account of its marked advantages over our awkward pound, foot, acre, quart, bushel, etc., it has been standardized for all scientific work, and consequently the electrical units are based upon this more convenient system. In the same manner that our money system greatly facilitates calculations by being based on the multiples of ten (namely, mil, cent, dime, dollar and eagle) the metric system provides units for measurement of all physical quantities which facilitate simple calculations involving these quantities.

fore, equal to 1000 cubic centimeters. It can be remembered as being a little larger than our quart.

The measurement of **mass** is based upon the **gram,** a very small unit and approximately equal to the mass of one cubic centimeter of water. It can be remembered as equal to one-fifth of our five-cent piece. In other words, a U. S. five-cent piece weighs 5 grams. The kilogram or 1000-gram weight is more commonly used. It can be best remembered as being a little larger than two pounds.

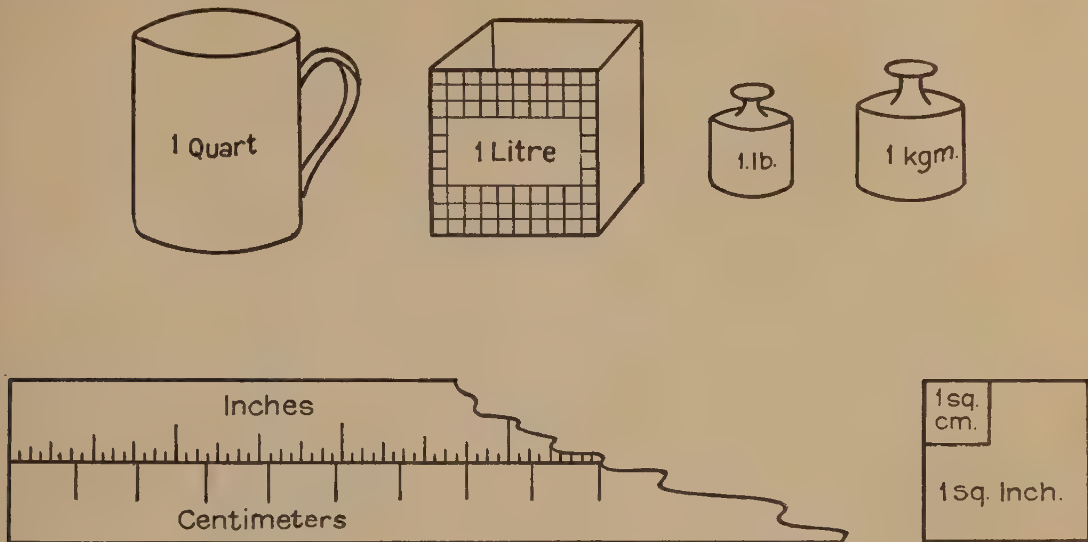



*Fig. 1—Comparison of English and Metric Units*

A system of prefixes is used in the metric system to indicate multiples of ten or decimal parts. This is illustrated in Table I, which gives the metric units for measurements of length.

The measurement of volume and liquid capacity is based upon the litre, which is a cube with each dimension ten centimeters in length. It is, there-

TABLE I

| METRIC UNITS OF LENGTH | |
|---|---|
| **Unit** | **Decimal** |
| 1 **Millimeter** | **.001** meter |
| 1 **Centimeter** | **.01** meter |
| 1 **Decimeter** | **.1** meter |
| 1 Meter | |
| 1 **Dekameter** | **10.** meters |
| 1 **Hectometer** | **100.** meters |
| 1 Kilometer | **1000.** meters |

There is only one system for measuring **time,** and the **second** has the same meaning in the scientific system as in our system.

Temperature is based upon the Centigrade scale instead of the Fahrenheit wherever the metric system is used. Zero degrees on the Centigrade scale corresponds to freezing point or 32 degrees on the Fahrenheit scale; 100 degrees on the Centigrade scale is the temperature of boiling water and corresponds to 212 degrees on the Fahrenheit scale. All intermediate degrees are proportional, which means that one degree Fahrenheit is equal to five-ninths degree Centigrade.* Figure 2 illustrates the thermometer showing both scales.

Table II gives the conversion factors between the English and metric systems for the units of various

*For converting temperatures from Fahrenheit to Centigrade the above relations may be expressed as a formula—

$$C^\circ = (F^\circ - 32)\ 5/9$$

and for converting Centigrade to Fahrenheit—

$$F^\circ = (C^\circ \times 9/5) + 32$$

# TABLE II

| RELATION BETWEEN METRIC AND ENGLISH UNITS | | | | | | |
|---|---|---|---|---|---|---|
| | Conversion from Metric to English | | | | Conversion from English to Metric | |
| Quantity | Name | Abbreviation | Value | English equivalent | Name | Metric Equivalent |
| TIME | Second | sec. | (Same in both systems) | | second | (Same in both systems) |
| LENGTH | centimeter<br>meter<br>kilometer | cm.<br>m.<br>km. | .01 meter<br>—<br>1000 meters | .39 inch<br>1.094 yards<br>.625 mile | inch<br>foot<br>yard<br>mile | 2.54 cm.<br>.305 meters<br>.915 meters<br>1.609 kilometers |
| MASS | gram<br>kilogram | gm.<br>kg. | —<br>1000 grams | .035 ounce (avoir.)<br>2.204 pounds | ounce<br>pound | 28.35 grams<br>.454 kilograms |
| AREA | square-centimeter<br>square-meter | sq. cm.<br>sq. m. | | .155 sq. in.<br>1.2 sq. yd. | square-inch | 6.45 sq. cms. |
| VOLUME | cubic centimeter<br>litre | cu. cm. | .001 litre<br>1000 cu. cms. | .061 cu. in.<br>1.06 quarts | cubic-inch<br>cubic-foot<br>gallon | 16.39 cu. cms.<br>28.3 litres<br>3.8 litres |
| FORCE | dyne (seldom used)<br>gram (of force)<br>kilogram (of force) | | .00102 gram<br>980 dynes | .035 ounce (of force)<br>2.20 pounds (of force) | pound (of force) | .454 kilograms (of force) |
| WORK | erg (seldom used)<br>joule | | 1 dyne-centimeter<br>10,000,000 ergs | .738 ft. lbs. | foot-pound | 1.35 joules |
| HEAT (Energy) | gram-calorie<br>large-calorie | gm.-cal. | gm. of water 1°C<br>1000 calories | 3.087 ft.-lbs.<br>3.963 B.t.u.'s | British thermal unit | 1055 joules<br>255 gram-calories |
| POWER | watt<br>kilowatt | kw. | joule per second<br>1000 watts | .74 ft.-lb. per sec.<br>1.34 horse power | horse power | 746 watts or<br>¾ kw. approximately |

Note:—The decimal fractions in the above table are not carried further than is essential for the applications made in this text.

physical quantities. Included in this table are several units that have not been discussed in the preceding pages, such as watt, dyne and joule, but the significance and use of such units is explained in the body of the text. Particularly important from our point of view are the relations between the watt or kilowatt and the horse power, and between the joule and the foot-pound.

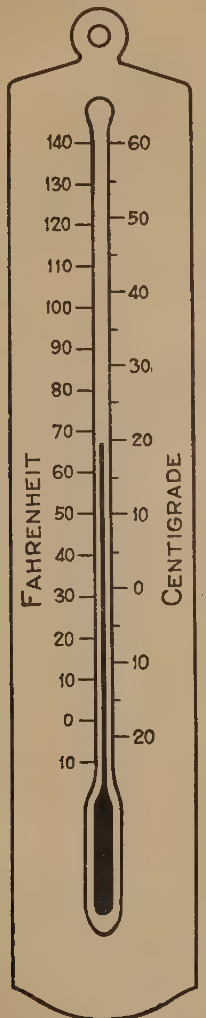



*Fig. 2—Comparison of Fahrenheit and Centigrade Scales*

### 11. Electrical Units

All of the practical units as well as some of the so-called scientific or absolute units for measuring electrical and magnetic quantities are defined and discussed in the body of the text.

There are three systems of units for measuring such quantities, the utility of each depending upon the nature of the calculations or measurements to be made. In general, except for certain kinds of theoretical calculations and laboratory experimentation, the familiar practical system is to be preferred.

The other two systems are the c.g.s. (centimeter-gram-second) electrostatic system and the c.g.s. electromagnetic system. The first of these systems is based on a consideration of electric charges and electric or electrostatic fields. As is well known electric charges or so-called "static electricity" may be produced on the surface of substances such as amber, rubber or glass by rubbing them vigorously with dry silk or fur. Such charges are accompanied by an electric or "static" field of force which, acting in the space around a charged body causes it to attract non-charged bodies such as small bits of paper and to attract or repel other charged bodies depending on whether the other bodies are charged with electricity of the opposite or the same sign. An electric field is always present wherever electricity is moving or tending to move. The electrostatic unit of charge or quantity of electricity is that possessed by each of two bodies which repel or attract each other with a force of one dyne when the bodies are one centimeter apart. This definition depends upon the arbitrary selection of unity as the dielectric constant of air at 0°C. The electrostatic unit of charge is a very small one, one coulomb being equal to $3 \times 10^9$ electrostatic units. From this the relationships between other electrostatic units and the corresponding practical units may be determined; for instance, the electrostatic unit of current is equal to $1/3 \times 10^{-9}$ amperes, the electrostatic unit of E.M.F. equals 300 volts, etc.

The c.g.s. electromagnetic system of units is developed from a consideration of magnetism and magnetic fields of force. Its fundamental definition, as given in the text, is that of the unit of magnetic pole strength, i.e., unit pole strength is that possessed by each of two magnetic poles that repel or attract each other with a force of one dyne when placed one centimeter apart. This definition depends upon the arbitrary selection of unity as the permeability of air at 0°C. The c.g.s. electromagnetic unit of E.M.F. is equal to $10^{-8}$ volts, while the electromagnetic unit of current equals 10 amperes. Other relationships between electromagnetic and practical units may be derived from these.

## APPENDIX II

### CIRCUIT DIAGRAM READING

A casual glance at a complicated telephone circuit drawing often leads the student to think that circuit reading is like a strange language acquired only by the most difficult study. He is confronted with a maze of apparatus parts connected by a complex entanglement of wires, and he despairs at the thought of memorizing hundreds of such circuits, each different from the others. Fortunately, this impression is more or less of an illusion. Though circuit reading is somewhat of a "knack", it depends for the most part upon skill to be acquired by learning the underlying principles step by step. Furthermore, while the best telephone men may diligently study these principles and apply them in practice, they never attempt to memorize circuit drawings. The large number of complicated circuits that are essential to the proper handling of telephone service can never be mastered in this way.

Accordingly, the following hints are given not as a key to every telephone circuit, but as a review of the underlying principles and as a recommended procedure for those not familiar with toll central office circuits:

(a) **Learn the principles of current flow including Ohm's and Kirchoff's Laws.**

(b) **Memorize the conventional circuit symbols for the commonly used units of telephone apparatus.**

(c) **Learn the functions of the elementary apparatus parts**—such as transmitter, receiver, condenser, ringer, induction coil, jack, key, relay, etc.

(d) **Start with very simple circuits and step by step take up more complicated circuits.** For instance, study Figures 7, 10, 17, 20, 81, 111, 112, 113, 119, 124, etc. of the text in the order given.

(e) **Remember that voice currents are very feeble alternating currents ranging in frequency somewhere between 200 and 3000 cycles, that ringing currents are alternating currents of 20 cycles or 135 cycles, and that the majority of relays are operated with direct currents.** On most drawings, the direct path of flow of voice currents is shown by heavy solid lines and the path for direct or ringing currents when not over the same conductors as voice currents is shown by light lines.

(f) **Bear in mind that direct currents will not flow through condensers and will flow through retardation coils and that alternating currents will effectively flow through condensers but are greatly reduced in their flow through retardation coils. Also, that direct current will not flow from one winding to another of an induction coil, repeating coil or transformer, and that alternating currents will flow, or to be more exact, are induced across from one winding to another of these coils.**

(g) **Learn first the purpose of operation, or in other words, that which the circuit is designed to accomplish.** For example, in Figure 113 of the text we might say that the circuits shown are designed to permit local telephone connections where one operator can establish all connections and the circuit design must permit common battery single position operation as follows:

> Subscriber takes receiver off hook and subset circuit in conjunction with line circuit must give operator signal by lighting lamp in face of switchboard in front of her. Operator must be able to answer subscriber by connecting her telephone set to some one of her cord circuits and connecting this cord circuit to calling party's line. Line circuit must contain relay features which will extinguish lamp when operator makes this connection. Cord circuit must permit operator to make similar connections to called party's line and to ring called party. Ringing current must not reach ear of operator or calling party. Operator must have signal associated with cord circuit that will tell her when called party has answered and when both parties are through talking and hang up. The system must be so designed as to provide direct current over line to subscribers' telephones for transmitter supply. The circuits must be designed to give an efficient voice current path from one subscriber to the other and from each subscriber to operator. Keys must be provided to permit operator to disconnect her head set from, or connect her head set to, cord circuit at will, thereby permitting her to handle connections with other cord circuits while two particular subscribers are talking.

We thus have the detailed performances for which the circuit must be designed. These are requirements for mechanical and electrical features that should be provided in a somewhat automatic manner. Knowing these, or in other words, knowing the operating procedure for establishing connections between two common battery subscribers, each part of the circuit will stand out as having a specific purpose and make circuit reading comparatively simple.

(h) **Get an approximate mental picture of the layout of the various apparatus parts.** For example, in Figure 113, we may think of the transmitter, receiver and hook switch in the telephone desk stand located on a table or desk at the subscriber's office or residence; the condenser, induction coil and bell located in the bell box at the subscriber's office or residence; the protector and relay equipment of the subscriber's line circuit located in the central office terminal room; the jack and lamp located in the face of the switchboard in front of the operator; the cord circuit equipment located somewhere in the switchboard position with the plugs, keys and supervisory lamps of this circuit in the key shelf where the supervisory lamps are visible and the plugs and keys are readily accessible.

(i) **Do not attempt to read wiring diagrams.** These are intended to assist the wireman in making the proper connections of cable pairs and other wires to the apparatus terminals and are not intended for circuit study. Make sure that the circuit drawing is a schematic or theory drawing and not a wiring diagram.

(j) **Learn thoroughly the operation of a few important telephone circuits pertaining to your particular branch of telephone work.**

(k) **If the circuit is a difficult and unusual one, ask someone to explain it to you in preference to following a written explanation of it.**

# APPENDIX III

## CONSTRUCTION AND USES OF CURVES

The use of graphical charts or curves is usually the most convenient and effective method of presenting data where two interdependent variables are involved. Such charts and curves are in most cases more readily understood than the corresponding mathematical equations and are not only easier to follow but take up less space than tables.

Any relationship between two variables, such for instance as $y = ax$, where y varies as x varies (or is said to be a "function of x") may be clearly pictured on a simple plane chart where one variable, say x, is plotted on a horizontal scale and the other variable, y, is plotted on a vertical scale. The two

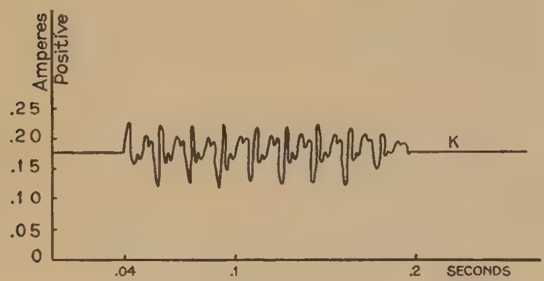



*Figure 1*

scales do not need to be alike, although each one must itself be uniform. Thus, Figure 1 shows the rather complex relationship between time and the current in the primary of a telephone subset induction coil when a certain vowel sound is spoken into the transmitter. Here we have a horizontal scale representing time, beginning at some instant designated as zero time and charted to the right in graduations of tenths of seconds and a vertical scale representing current values charted upward in graduations of .05 amperes. Thus curve K shows all values of the current in the circuit for the interval of time considered and conveys a better and more complete idea of what is actually taking place in the circuit than could be expressed in words. During the interval of time between zero and .04 seconds, i.e., during the first .04 seconds considered, there is a steady current through the transmitter and induction coil primary of .18 amperes; but beginning at the instant represented by .04 seconds a vowel sound is spoken into the transmitter and its resistance is alternately lowered and increased causing fluctuations in the current value which are represented by the irregular portion of the curve between .04 and .2 seconds. The value of the current could of course be charted over any period of time but in this case we have sufficient values to show clearly the effect on the transmitter current of a certain spoken vowel.

The chart of Figure 1 is adequate for showing the magnitude of a current varying with time. Frequently, however, cases are encountered where it is desirable to show not only the magnitude of the current but its direction as well. To take care of this a convention has been adopted that values plotted upward on the vertical scale shall be con-

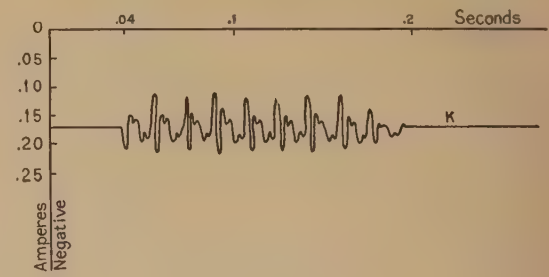



*Figure 2*

sidered as positive and values plotted downward as negative. Similarly, values plotted to the right on the horizontal scale are positive and to the left, negative. Thus, if the battery causing the current in Figure 1, which we have considered positive, were reversed, we would have a current in the opposite or negative direction and our current-time diagram would be that of Figure 2. In the same way, to represent an alternating current we may

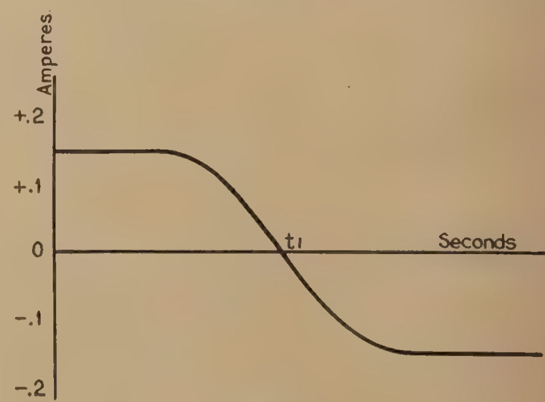



*Figure 3*

use a current-time curve such as that shown by Figure 3, which beginning at zero time represents a sequence of positive current values decreasing to zero value after the time $t_1$, and followed by a sequence of negative current values (i.e., current in the opposite direction) increasing from zero at time $t_1$.

Obviously curves such as those illustrated and discussed above may be used for other purposes than charting the relation between current and time. They may quite as frequently be used to chart relations between voltage and time or, in fact, between any two quantities that are so related that one is a function of or is dependent on the other. There are frequent occasions, also, for charting the relationship between two quantities both of which may be either positive or negative. For this purpose a diagram known as a "complete retangular coordinate diagram" such as that illustrated by Figure 4 is used. The hysteresis curves shown by Figures 42 and 43 in Chapter IV of the text are good examples of diagrams of this kind.

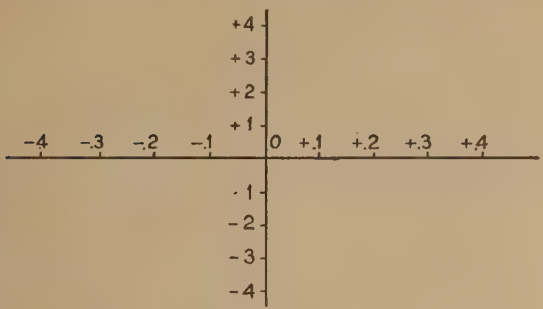



*Figure 4*

A curve charted so as to show the relation between two quantities, one of which is time, may be used not only to determine values at any specific instant but also to determine the **rate of change** of the value at any instant. The curve of Figure 5, for instance, which represents the relation between distance covered by some moving object and the time required to cover this distance, will tell us how far the object is from the starting point at any instant and also the speed or **rate of change of distance** at that instant. This speed or rate of change

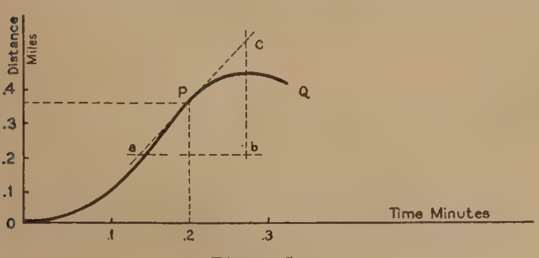



*Figure 5*

of distance is defined as the **slope** of the curve at the designated instant. Thus, the speed at which the moving object of Figure 5 is travelling .2 minutes after it leaves the starting point may be determined by finding the slope of the curve at the point P, where a vertical line drawn upward from the .2 minute graduation on the time scale intersects the curve.

The slope may be determined by drawing through the point on the curve a straight line **tangent** to or having the same direction as the curve at the point and constructing on this straight line a right triangle of any convenient size but having one leg, as **bc**, vertical and the other, **ab**, horizontal; then the value of **bc** measured on the vertical scale of the chart divided by the value of **ab** measured on the horizontal scale is the slope of the curve at the point P. This quantity is distance divided by time and therefore is a measure of rate of change of distance or, in more useful terms, the **speed** at which the body is moving .2 minutes after it leaves the starting point. At this point the speed is positive because the distance is becoming greater and the motion of the body is away from the starting point. Therefore, we may say that when the slope of the curve is upward from left to right, it is positive and represents a positive rate of change. On the other hand, if the body ceases to move away from the starting point and returns toward it, it may be said to have negative speed. Such a condition is illustrated by point "Q" of Figure 5 and here the slope of the curve is downward from left to right and is negative.

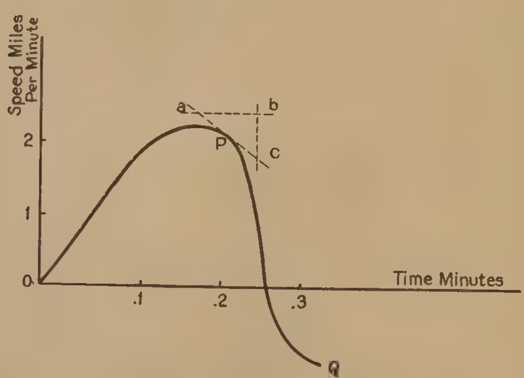



*Fig. 6—Speed-Time Curve. Slope is Acceleration*

Now if we calculate the speed for a sequence of points along the curve of Figure 5 by the method just described and chart these values against time, we obtain the curve of Figure 6. In this case the slope of the curve gives us rate of change of speed or **acceleration.** Thus the acceleration at the point P of Figure 6, or .2 minutes after the body starts to move, may be measured by drawing a tangent to the curve at the point, constructing a triangle as shown, and dividing the length of the line **bc** as projected on the speed scale by the length of the line **ab** as projected on the time scale. As before, we have positive acceleration meaning increasing speed which is represented by positive slope, and negative acceleration meaning decreasing speed or "slowing down", which is represented by negative slope. At point P the acceleration is negative since the body is slowing down prior to reversing its direction of motion and returning toward the starting point.

## WAVE MOTION FREQUENCY SCALES

### 1. Vibratory Motion

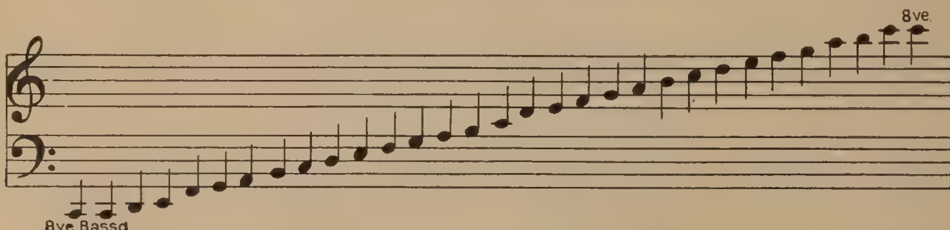
Manifestations of vibratory or wave motion are common in all nature and many forms take place about us continuously. Perhaps the most obvious form is the water wave which everyone has observed to be a form of vibratory motion. By means of condensations and rarefactions of the atmosphere, which are as truly a form of wave motion as the water wave, we experience the sensation called sound. By virtue of still another form of wave motion consisting of a vibration in the mysterious substance which fills all space, called "ether", we recognize the color of some brilliant object. To go further, if this vibration is of a certain particular frequency the color registered by the retina of the eye may be red, but if nearly twice this particular frequency we are conscious of violet color instead of red. In an electrical conductor, we may think of an electrical current flowing first in one direction and then in the other, as another example of wave phenomena not altogether different from that of light, and although belonging to an entirely different category, similar in some respects to that of sound or even water waves.

quencies are shown by tens, hundreds and thousands instead of as notes of the musical scale. This figure also extends the frequencies to the absolute limits of human hearing or the so-called "limits of audibility". Vibrations coming within the limits of this scale are referred to as **audio-frequencies,** and an alternating electrical current having a frequency, for example, of 1,000 cycles, would be carrying the equivalent of a monotonous pure tone lying somewhere between C″ and C‴ of the musical scale.

Figure 3 illustrates a scale of ether vibrations which transmit light, radiated heat, and the electromagnetic waves of wireless telephony and telegraphy. This scale is likewise arranged by graduations proportional to octaves rather than the constant separation of the numerical frequency values. The number shown opposite each graduation corresponds to frequency.

### 2. Alternating Current Frequency Scales

All alternating current frequencies that have any general application in practice, can be grouped and graphically pictured similarly to the foregoing scales for sound and light. We, thus, have represented in Figure 4 a chart of the alternating current




| | C₁ | C | D | E | F | G | A | B | c | d | e | f | g | a | b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Relative Pitch | $\frac{1}{2}$ | 1 | $\frac{9}{8}$ | $\frac{5}{4}$ | $\frac{4}{3}$ | $\frac{3}{2}$ | $\frac{5}{3}$ | $\frac{15}{8}$ | 2 | $\frac{9}{4}$ | $\frac{5}{2}$ | $\frac{8}{3}$ | 3 | $\frac{10}{3}$ | $\frac{15}{4}$ |
| Frequencies | 32 | 64 | 72 | 80 | $85\frac{1}{3}$ | 96 | $106\frac{1}{3}$ | 120 | 128 | 144 | 160 | $170\frac{1}{3}$ | 192 | $213\frac{1}{3}$ | 240 |

| | c′ | d′ | e′ | f′ | g′ | a′ | b′ | c″ | d″ | e″ | f″ | g″ | a″ | b″ | c‴ | $c^{IV}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Relative Pitch | 4 | $\frac{9}{2}$ | 5 | $\frac{16}{3}$ | 6 | $\frac{20}{3}$ | $\frac{15}{2}$ | 8 | 9 | 10 | $\frac{32}{3}$ | 12 | $\frac{40}{3}$ | 15 | 16 | 32 |
| Frequencies | 256 | 288 | 320 | $341\frac{1}{3}$ | 384 | $426\frac{2}{3}$ | 480 | 512 | 576 | 640 | $682\frac{2}{3}$ | 768 | $853\frac{1}{3}$ | 960 | 1024 | 2048 |

*Fig. 1—Musical Scale*

Audible sound is defined as a disturbance in the atmosphere whereby a form of wave motion is propagated from some source with a velocity of approximately 1,075 feet per second, the transmission being by means of alternate condensations and rarefactions of the atmosphere in cycles having a fundamental frequency ranging somewhere between 16 cycles per second and 32,000 per second. In Figure 1, we have a scale arranged by frequencies corresponding to periodic recurring octaves. It shows the musical staff notation and the frequencies of the notes vary as numbers whose logarithms can be shown as a simple progressive scale. Figure 2 shows another sound scale as a simple table of frequencies again arranged by graduations corresponding to octaves or logarithms. Here, however, fre-

frequencies used in both power and communication work. This chart naturally includes many of the same frequency values shown in the foregoing scales, because frequencies identical in value with those of sound are commonly used in telephone circuits and frequencies used in wireless telephony and telegraphy are also often used for various wire applications, such as carrier. A study of Figure 4 gives us the entire field of use of electricity in the alternating current form, so ordered that we see at a glance the wide range of frequency values and their adaptability to different utilitarian applications.

This chart is divided into four columns, representing four different fields of use of electricity.

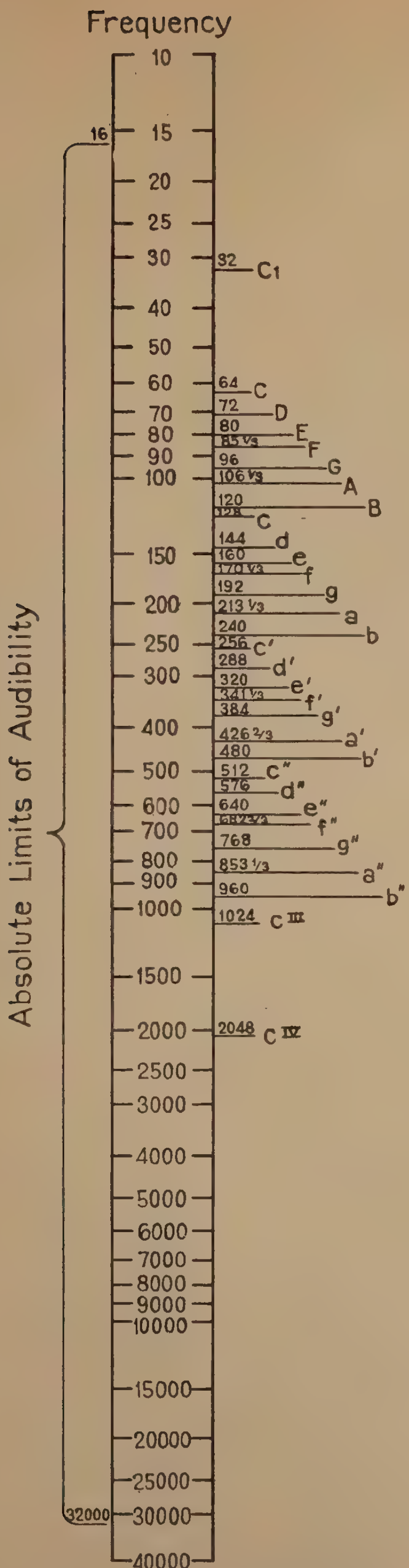



*Fig. 2—Logarithmic Musical Scale*

The first column is headed "Power Work", the second "Telegraph", the third "Telephone", and the fourth "Telephone Signaling". Adjacent to each column, either on the right or left, is a scale of frequencies which is again arranged by octaves with the actual frequency values shown, or in other words, is a logarithmic rather than an arithmetic scale, which gives all frequencies between 10 cycles and 15,000,000 cycles per second.

In the "Power" column we find a bracketed note opposite 25 cycles which covers a widely used frequency in power work when alternating current railways are involved and lighting is a secondary consideration. But sixty cycles is indicated as the standard power frequency used most extensively in power work. Each standard has its advantages. Alternating current machinery designed for 25 cycles need not be designed to operate at high speeds, and in some cases permits better power control than 60 cycles. One case in particular is that of alternating current railways. On the other hand, 25 cycles is not desirable for lighting inasmuch as the ordinary tungsten filament will sufficiently cool between positive and negative current peaks of the cycle (or in the 1/50th second interval) to cause the light to "flicker". The 60 cycle system is ideally adapted to lighting and for most applications is well adapted to power work, but has certain limitations in this connection which make the 25 cycle systems preferable for applications such as those already mentioned.

Near the bottom of this column is a note explaining that lightning frequencies range from a few hundred thousand cycles to the higher wireless frequencies. Of course, all exposed power lines and communication lines as well as radio receiving and transmitting circuits are subject to lightning hazards, and protection design is an application to circuits involving these frequencies.

The second column of Figure 4 headed "Telegraph", covers four classes of telegraph transmission. First, the more common system designated "ordinary telegraph", including the familiar grounded neutral and duplex systems and metallic cable systems; second, the voice frequency carrier current telegraph system; third, the superposed carrier current telegraph; and fourth, the radio telegraph. The first application, or the more common telegraph system which makes and breaks a direct current circuit is usually thought of as a direct current system, but considering the rapidity of the makes and breaks and the wave-like nature of the telegraphic pulses, we have an approximation to an alternating current transmission that we could describe as a telegraphic band of frequencies beginning at zero and shading into about 25 cycles.

The other applications make and break a steady flow of alternating current rather than direct current. The voice frequency cable carrier system makes use of a series of frequencies beginning at 425 cycles and extending to 2295 cycles or higher. By this means ten or more telegraph channels are secured over a four-wire cable circuit with a separation in frequency between channels of 170 cycles.

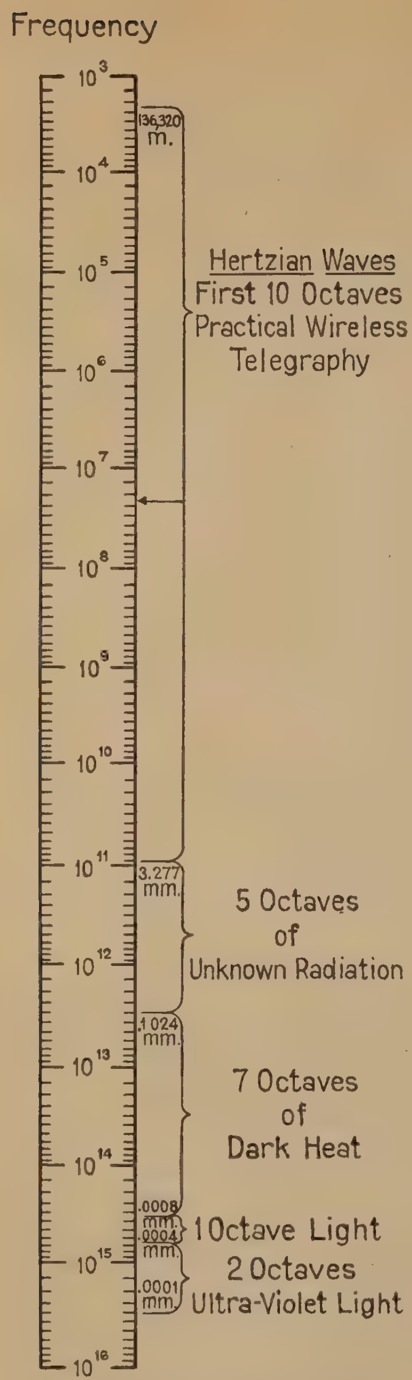



*Fig. 3—Logarithmic Ethereal Scale*

The use of the four-wire circuit permits transmitting in both directions at the same frequency. It will be noted, however, that the frequencies used in this telegraph application are within the ordinary voice range so that a cable circuit used for a voice frequency carrier telegraph system cannot at the same time be used as a telephone circuit.

Due to the greater cost of the wire facilities it is not economical to operate the voice frequency carrier system on open wire circuits since this would not permit the use of the facilities as telephone circuits. Non-loaded open wire circuits, however, are capable of transmitting much higher frequencies than are cable circuits. This feature makes possible the superimposing on an open wire telephone circuit a higher frequency carrier telegraph system. As shown in Figure 4, this carrier system uses frequencies between 3,300 and 10,000 cycles, ten frequencies being used for transmitting West to East and ten higher frequencies for transmitting East to West. The use of different frequencies for transmitting in the two directions makes possible the application of the system on an ordinary two-wire circuit.

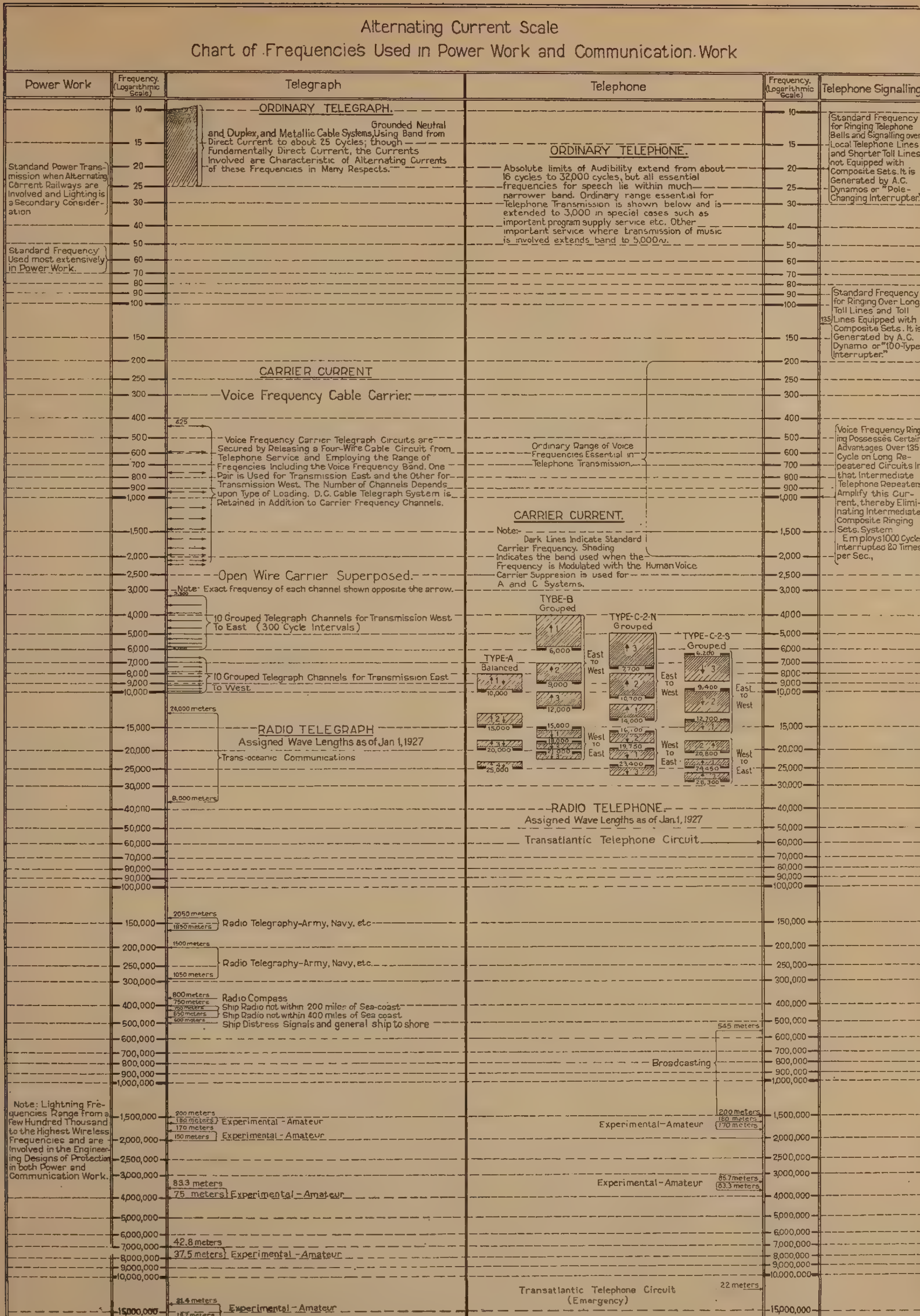
The radio telegraph employs frequencies from a little more than 10,000 cycles to more than 15,000,000 cycles. The wave lengths corresponding to any radio frequency (or any ethereal vibration whatsoever) are calculated from the formula,

$$\lambda = \frac{300{,}000{,}000}{f}$$

where "λ" is the symbol for wave length in meters and "f" is the frequency. This is evident from the known speed of ethereal waves, which is 300,000,000 meters per second, since the number of wave lengths in one second (or frequency) times the length of one wave must equal the distance traveled in one second, or 300,000,000 meters.

Wave lengths are assigned for radio telegraph and radio telephone communication through Government or International Conference regulation and are accordingly subject to change. The longer wave lengths are commonly used where considerable power is involved, i.e., where the distance of transmission is comparatively great. This accounts for the band of frequencies between the 24,000 meter wave length and the 8,000 meter wave length being assigned to trans-oceanic communication, and the shorter wave lengths being assigned to amateur use and short distance transmission. The short wave lengths are being more and more generally used for long distance transmission, however, as under favorable conditions transmission over great distances can be secured with much less power by means of very short waves.

Alternating current frequencies employed in **telephone transmission** are in every case "bands" representing the range of voice frequencies essential for intelligibility in a telephone conversation, and in this respect the application is unlike that of telegraph. The ordinary telephone circuit, to give good intelligibility, must employ a band from 200 to 2,000 cycles, as shown by the bracket in this



Alternating Current Scale
Chart of Frequencies Used in Power Work and Communication Work
Power Work
Frequency (Logarithmic Scale)
Telegraph
Telephone
Telephone Signalling
ORDINARY TELEGRAPH.
Grounded Neutral and Duplex, and Metallic Cable Systems, Using Band from Direct Current to about 25 Cycles; though Fundamentally Direct Current, the Currents Involved are Characteristic of Alternating Currents of these Frequencies in Many Respects.
ORDINARY TELEPHONE.
Absolute limits of Audibility extend from about 16 cycles to 32,000 cycles, but all essential frequencies for speech lie within much narrower band. Ordinary range essential for Telephone Transmission is shown below and is extended to 3,000 in special cases such as important program supply service etc. Other important service where transmission of music is involved extends band to 5,000~.
Standard Frequency for Ringing Telephone Bells and Signalling over Local Telephone Lines and Shorter Toll Lines not Equipped with Composite Sets. It is Generated by A.C. Dynamos or "Pole-Changing Interrupter."
Standard Power Transmission when Alternating Current Railways are Involved and Lighting is a Secondary Consideration
Standard Frequency Used most extensively in Power Work.
Standard Frequency for Ringing Over Long Toll Lines and Toll Lines Equipped with Composite Sets. It is Generated by A.C. Dynamo or "100-Type Interrupter."
CARRIER CURRENT
Voice Frequency Cable Carrier
Voice Frequency Carrier Telegraph Circuits are Secured by Releasing a Four-Wire Cable Circuit from Telephone Service and Employing the Range of Frequencies Including the Voice Frequency Band. One Pair is Used for Transmission East and the Other for Transmission West. The Number of Channels Depends upon Type of Loading. D.C. Cable Telegraph System is Retained in Addition to Carrier Frequency Channels.
Ordinary Range of Voice Frequencies Essential in Telephone Transmission
Voice Frequency Ringing Possesses Certain Advantages Over 135 Cycle on Long Repeatered Circuits in that Intermediate Telephone Repeaters Amplify this Current, thereby Eliminating Intermediate Composite Ringing Sets. System Employs 1000 Cycles Interrupted 20 Times per Sec.,
CARRIER CURRENT.
Note:- Dark Lines Indicate Standard Carrier Frequency. Shading Indicates the band used when the Frequency is Modulated with the Human Voice. Carrier Suppression is used for A and C Systems.
Open Wire Carrier Superposed.
Note- Exact frequency of each channel shown opposite the arrow.
10 Grouped Telegraph Channels for Transmission West To East (300 Cycle Intervals)
10 Grouped Telegraph Channels for Transmission East To West.
TYPE-A Balanced
TYBE-B Grouped
TYPE-C-2-N Grouped
TYPE-C-2-S Grouped
East to West
West to East
RADIO TELEGRAPH
Assigned Wave Lengths as of Jan 1, 1927
Trans-oceanic Communications
24,000 meters
8,000 meters
RADIO TELEPHONE.
Assigned Wave Lengths as of Jan. 1, 1927
Transatlantic Telephone Circuit
Radio Telegraphy-Army, Navy, etc.
Radio Telegraphy-Army, Navy, etc.
Radio Compass
Ship Radio not within 200 miles of Sea-coast
Ship Radio not within 400 miles of Sea coast
Ship Distress Signals and general ship to shore
Broadcasting
545 meters
200 meters
Note: Lightning Frequencies Range from a few Hundred Thousand to the Highest Wireless Frequencies and are Involved in the Engineering Designs of Protection in both Power and Communication Work.
Experimental - Amateur
Experimental - Amateur
Experimental-Amateur
83.3 meters
75 meters
Experimental - Amateur
Experimental-Amateur
85.7 meters
83.3 meters
42.8 meters
37.5 meters
Experimental - Amateur
Transatlantic Telephone Circuit (Emergency)
22 meters
21.4 meters
18.7 meters
Experimental - Amateur


*Figure 4*

column. To preserve quality, the range of frequencies from 500 to 1,800 should be transmitted with very little distortion, and the distortion that is permissible for other frequencies will, of course depend upon the nature of the service. For example, in program supply service where quality is very essential, it is necessary to extend the entire band of frequencies to include 3,000 cycles if only speech is to be transmitted, and to include 5,000 cycles if music is to be transmitted.

Carrier current telephone transmission is accomplished by "modulating" a single frequency with the band of voice frequencies. A typical case is the first channel on the type "A" system which represents a 10,000 cycle frequency varying to a lower value, which variation would represent the frequency of the voice. Thus, each carrier channel is shown as a band shading away from the designated value of the carrier frequency. It will be noted that the graphical representation of the bands is of decreasing width from the lower frequencies to the higher frequencies. This means that each band will have a width corresponding to the range of voice frequency. On account of the frequency being plotted on a logarithmic scale, the scalar width of the band represents the ratio of the band to the carrier frequency. In other words, a 2,000 cycle band at 20,000 cycles would represent only a 10% variation in the carrier frequency, while a 2,000 cycle band with a 6,000 carrier frequency would represent a 33-1/3% variation.

In so far as the frequencies that may be employed are concerned, radio telephone transmission is not essentially different from radio telegraph transmission. The assignment of wave lengths in this service, however, has been somewhat restricted, but more as a matter of regulation than for scientific reasons. This gives the radio telegraph which is the older of the two services a standing priority. On account of this limitation the frequencies most widely used for radio telephony at the present time comprise a group between 200 meters and 545 meters, which group is assigned to broadcasting. Practically all private broadcasting stations employ wave lengths somewhere within this range. A second band of frequencies lying between the 100 meter wave length and the 150 meter wave length has likewise been assigned to radio telephone broadcasting service, but on account of certain disadvantages of the higher frequency values it has not been extensively used.

The recent development of the high powered vacuum tube has lead to telephone systems for long distance radio work employing amounts of power more nearly commensurate with high power telegraph systems. One such application is shown opposite the 60,000 cycle value of the scale which refers specifically to the joint trans-oceanic circuit of the American Telephone and Telegraph Company and the British Post-Office.

While **telephone signalling** is essentially a part of telephone communication service, it is, nevertheless, distinct from the transmission of the human voice. The fourth column of Figure 4 shows three telephone signalling systems. The standard ringing current for ringing telephone bells and signalling over local telephone lines as well as over toll lines not equipped with composite sets, has a comparatively low frequency of approximately 20 cycles, and is ordinarily referred to as "20-cycle ringing".

The 20 cycle current would naturally fall within the band of frequencies discussed in connection with "ordinary telegraph", which as has been explained, is essentially direct current, but shades into the alternating scale to about 25 cycles. Consequently, it would not be practicable to separate in the telephone office a 20 cycle ringing current from a telegraph current, and a ringing current of this frequency transmitted over composited telephone lines would interfere with the telegraph service. Conversely, telegraph currents would likewise interfere with signalling. For this reason a second frequency, well outside the ordinary telegraph range of frequencies, is required for ringing over composited circuits. The standard frequency value assigned for this use is 135 cycles.

On very long telephone circuits equipped with a number of through line telephone repeater sets at various intermediate points, there are advantages to be gained in eliminating the special apparatus which is required at each repeater point to relay the 135 cycle current around the telephone repeater circuit. This is necessary because the repeater set is ordinarily not designed to "pass" the 135 cycle frequency. Of course, the repeater is designed to amplify the band of frequencies representing the actual voice, and any ringing current within this range of frequencies would not only pass through the repeater but would at the same time be amplified. Such an arrangement would not require relaying equipment for the ringing current. This third ringing frequency is 1000 cycles interrupted 20 times per second, the latter feature being necessary in order that conversation over the circuit, which will ordinarily contain some 1000 cycle notes, will not operate the ringer.

In concluding the foregoing explanation of the various frequency values and frequency bands in general use, it should be remembered that this description is neither complete nor fundamentally descriptive of the distinction between various alternating current applications. Though the frequency scale illustrates in one sense characteristic differences in the currents, it should be remembered that other characteristic differences such as energy values might illustrate an equally wide diversification. Furthermore, the use of a single frequency does not mean that no consideration must be given to the nature of other frequencies which may indirectly become involved in the same application. To illustrate, a 60 cycle, 3-phase power line when unbalanced has a residual current flow of 180 cycles, and the same power system with imperfect sine wave form may carry harmonics which give a band

of frequencies extending through the voice frequency range, resulting in serious inductive interference with communication circuits paralleling the power lines. Another case is radio telegraph transmission. While employing a single wave length, this must have a sufficiently accurate sine wave form so that it will not radiate harmonics which would interfere with radio communications employing other wave lengths. The application of alternating currents of a single frequency or a single band of frequencies, therefore, may and actually does in the majority of instances, involve the suppression of other frequencies as well as the use of the individual frequency.

### 3. Wave Analysis

It is known that the characteristic wave forms for vowel sounds are complex waves rather than sine waves of a designated frequency, and that alternating currents which represent the tones of the human voice are seldom, if ever, a simple sine wave. The same may be said for many other cases of alternating current transmission. We would be hopelessly involved if we should attempt to deal with any current wave shape that might be encountered as distinct and apart from the sine wave, which is the basis of most alternating current circuit calculations. Fortunately, for all practical cases, **any steady state alternating current wave form, regardless of how irregular, may be considered as a series of sine wave currents being simultaneously transmitted.** That is to say, any irregular current wave shape can be analyzed or broken up into a series of sine wave shapes. This series can further be restricted to a fundamental frequency and multiples or harmonics of this fundamental frequency. For example, Figure 5 shows an irregular wave so analyzed, and by actually adding the successive and corresponding values of all the sine waves, we can chart the original and irregular wave shape.

The practical treatment of any irregular wave shape for electrical transmission, is, then, divided into two steps:

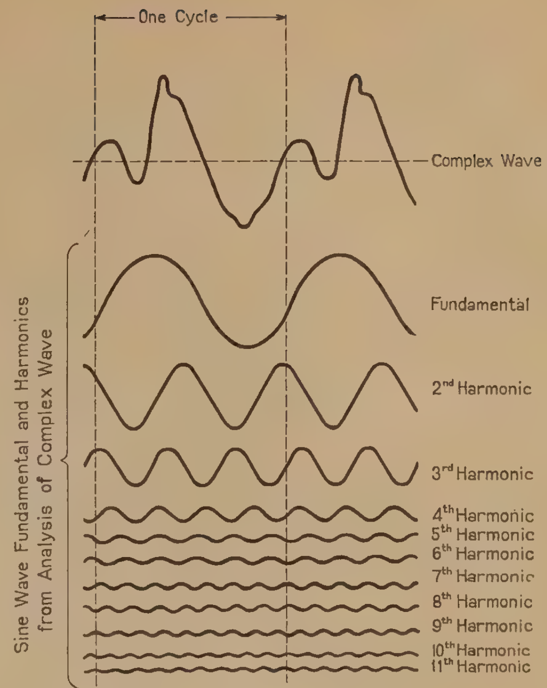



*Fig. 5—Analysis of Sound Wave (By Fourier's Theorem)*

a. **Analyze the wave shape into a fundamental sine wave and its harmonics.**

b. **Deal with each of these component sine waves individually.**

The actual mechanical analysis, such as that shown by Figure 5, is quite difficult, and while the analysis can be made from an "oscillogram", this is for the most part a combination of a laboratory process and involved mathematical calculations. For most purposes, however, we need be concerned with the concept only rather than with the actual analysis.

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